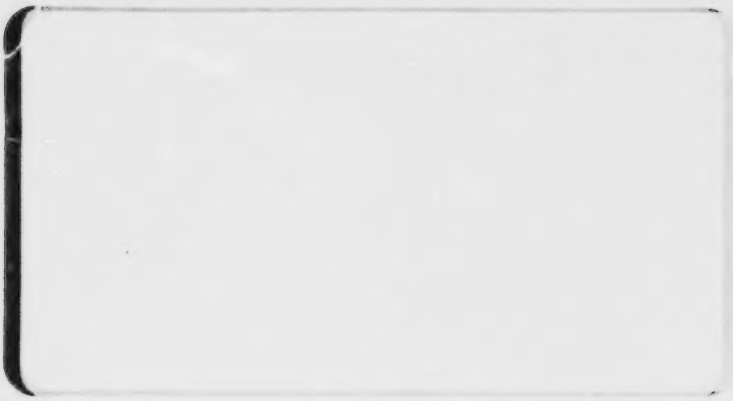

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# TECHNICAL MEMORANDUM IV

# ASSESSMENT OF ALTERNATIVE EVALUATION METHODS AND ALTERNATIVE STABILIZATION PRACTICES

'40pp

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THE TECHNOLOGY OF URANIUM TAILINGS COVERS
&
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THE STABILITY OF CONTROL STRUCTURES FOR URANIUM MILL TAILINGS

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MICROMEDIA

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This study was guided by the Scientific Authority, Mr. Grant Feasby, and his prompt and effective guidance, review and comment contributed largely to its successful completion.

## PREFACE

This technical memorandum is the fourth in a series of five technical memoranda which document the data, technology and evaluation studies undertaken to evaluate the long term stability of "Covers" and "Control Structures" for Canadian uranium mill tailings. The technical memoranda are:

| Technical Memorandum | Title |
|---|---|
| TMI | Canadian Uranium Tailings Deposits and Structures |
| TMII | Characteristics Relevant to Releases of Three Generic Canadian Uranium Tailings Sites |
| TMIII | Methodology for Stability and Release Rate Evaluation |
| TMIV | Assessment of Alternative Evaluation Methods and Alternative Stabilization Practices |
| TMV | Evaluation of Cover and Structure Stability on Three Generic Canadian Uranium Tailings Sites |

The conclusions reached and observations made as a result of these studies are summarized in two reports entitled:

REPORT 58901 THE TECHNOLOGY OF URANIUM TAILINGS COVERS

REPORT 58902 THE STABILITY OF CONTROL STRUCTURES FOR URANIUM MILL TAILINGS

This technical memorandum describes alternative cover technology, the assessment work done on alternative methods of long term stability evaluation and release rate estimation. In it the methodologies described in TM III are applied to typical Canadian deposits and structures with the object of determining the suitability and applicability of the technology to Canadian conditions.

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# TECHNICAL MEMORANDUM IV: ASSESSMENT OF ALTERNATIVE EVALUATION METHODS AND ALTERNATIVE STABILIZATION PRACTICES

## IV.1.0 ALTERNATIVE COVER TECHNOLOGY

### IV.1.1 SELECTION AND DESIGN OF SURFACE COVERS

The most cost and environmentally effective surface cover appropriate for any particular tailings deposit depends on a wide range of site specific factors. These include, but are not limited to, the nature of the tailings and associated pollutants, topographic, climatic and soil conditions, sensitivity of the surrounding environment, potential for revegetation or a water cover, and the availability of rock material. An approach to the selection and design of surface covers has been proposed by Beedlow, 1984. A modification of the flow diagram he proposed, which allows for water covers and the evaluation of infiltration, salt migration and frost heave is shown in Figure IV.1-1.

This flow diagram is fairly simplistic and does not allow for all the combinations or variations in cover types. It does serve to illustrate the data collection, evaluation and design process. The following description is a modification of that proposed by Beedlow.

Phase one consists of evaluating site conditions. For a given site, data on tailings, climate, soils, hydrogeology, hydrology, geomorphology, and vegetation are collected. The long-term vegetative potential for the site may then be determined by evaluating existing vegetative cover on soils that are available and desirable for use at the site. Expected climatic changes also need to be considered. Over the long-term, vegetation on the covered tailings can be expected to resemble that in the surrounding area where soils drainage and topography are similar. Therefore, the erosion rate of vegetated soils may be calculated. Site data on vegetation, climate, soils, and geomorphology is used to determine the erosive forces acting on the pile. Areas exposed to channel flooding or gully erosion may need riprap or other forms of engineered armour. Those not exposed to flooding and gullying can probably be stabilized by vegetation and/or unengineered rock covers. Based on the calculated erosion rates and criteria for stability, the adequacy of vegetation for surface protection can be determined.

In Canada the potential of a long term stable water cover may be evaluated as an alternative to vegetation. The potential of a water cover, as an economic alternative to vegetation, is dependent on having appropriate topographical conditions and excess water. The economic viability of such a cover should become apparent with a minimum of design and costing.

Determining the adequacy of vegetation is appropriate, because even if no surface treatment is applied, vegetation will become established in time. It may be possible to achieve acceptably short-time periods by simple measures such as contouring and draining the tailings. More complex actions such as chemical treatment of the surface tailings layers may still be more cost effective than cover placement. If vegetation is considered adequate, a preliminary revegetation plan is produced. If vegetation is

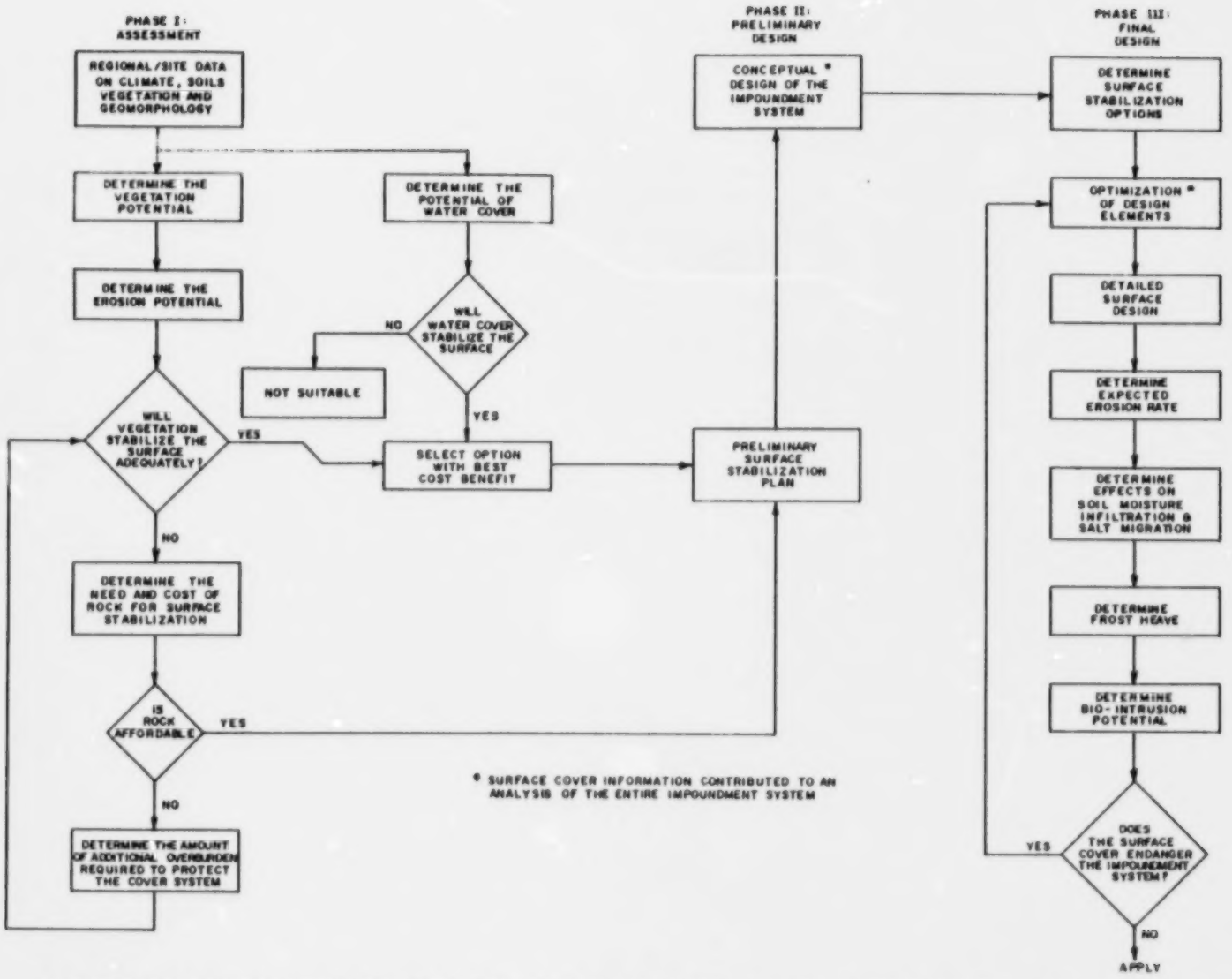

PHASE I: ASSESSMENT
REGIONAL/SITE DATA ON CLIMATE, SOILS VEGETATION AND GEOMORPHOLOGY
DETERMINE THE VEGETATION POTENTIAL
DETERMINE THE EROSION POTENTIAL
WILL VEGETATION STABILIZE THE SURFACE ADEQUATELY?
YES
NO
DETERMINE THE NEED AND COST OF ROCK FOR SURFACE STABILIZATION
IS ROCK AFFORDABLE
YES
NO
DETERMINE THE AMOUNT OF ADDITIONAL OVERBURDEN REQUIRED TO PROTECT THE COVER SYSTEM
DETERMINE THE POTENTIAL OF WATER COVER
WILL WATER COVER STABILIZE THE SURFACE
NO
NOT SUITABLE
YES
SELECT OPTION WITH BEST COST BENEFIT
PHASE II: PRELIMINARY DESIGN
CONCEPTUAL * DESIGN OF THE IMPOUNDMENT SYSTEM
PRELIMINARY SURFACE STABILIZATION PLAN
* SURFACE COVER INFORMATION CONTRIBUTED TO AN ANALYSIS OF THE ENTIRE IMPOUNDMENT SYSTEM
PHASE III: FINAL DESIGN
DETERMINE SURFACE STABILIZATION OPTIONS
OPTIMIZATION * OF DESIGN ELEMENTS
DETAILED SURFACE DESIGN
DETERMINE EXPECTED EROSION RATE
DETERMINE EFFECTS ON SOIL MOISTURE INFILTRATION & SALT MIGRATION
DETERMINE FROST HEAVE
DETERMINE BIO-INTRUSION POTENTIAL
DOES THE SURFACE COVER ENDANGER THE IMPOUNDMENT SYSTEM?
YES
NO
APPLY

FIGURE IV.1-1

FLOW DIAGRAM FOR DESIGNING INACTIVE MILL TAILINGS SURFACE COVERS (AFTER BEEDLOW, 1984, MODIFIED TO INCLUDE WATER COVERS, INFILTRATION, SALT MIGRATION AND FROST HEAVE).

judged to be inadequate for long-term erosion control on all or parts of the pile, other means must be used to prevent erosion damage. The next step is to determine the need and cost of suitable rock for covering the entire pile or portions of the pile exposed to high erosion rates. Some types of rock can be very effective in reducing erosion, but they may not be available locally. The cost of using rock covers is heavily dependent on the cost of excavating or quarrying and the distance it must be hauled.

If rock cover is feasible, a preliminary design using rock or a combination of rock and vegetative covers can be produced. If suitable rock is not available, the use of additional overburden, greater amounts or better quality topsoil, or recontouring the pile may reduce erosions rates. Once these options are determined, erosion potential is recalculated and again the adequacy of vegetation as a surface cover is evaluated. This process may require several iterations before a preliminary plan is produced.

The preliminary surface stabilization plan is intended to provide information and alternatives for surface cover design to those planning radon barriers, biobarriers and liners (if piles are moved). Once the overall containment system concept has been approved, a final design for surface covers can be produced.

The third phase of the design process begins by determining the options for surface stabilization available for the site. The cost and effectiveness of the alternatives are optimized in conjunction with other containment system components. Before the final design can be chosen, impacts of surface stabilization design on the functioning of the entire system must be evaluated in detail. Erosion rates are determined using site environmental data and engineering specifications. Effects of surface covers on infiltration soil moisture and salt migration should be determined, taking radon and biological barrier designs (and liners when appropriate) into account. For Saskatchewan, frost heave must be evaluated as this is crucially dependent on cover type. The risk, and possible effects of plant and animal intrusion resulting from the proposed surface cover must be evaluated at this time. If the consequences of surface cover design do not jeopardize the functioning of the system based on the above evaluations, then the design can be finalized. If the surface cover does jeopardize the functioning of the system, then alternative designs are considered. Again, several iterations of this process may be necessary.

The major benefit of the flow diagram approach is the flexibility it allows in designing surface covers. It does not specify types and amounts of cover material but requires only that designs provide adequate surface erosion control and not jeopardize the containment of toxic compounds. Adequate erosion control is, logically, that which is required to keep the protective layer intact for the design life of the containment system. A surface cover, therefore, can be any combination of untreated tailings, treated tailings, soil, rock and vegetation that is effective and economical.

### IV.1.2 VEGETATION COVER

Reclamation means the restoration of a site to an acceptable level of impact on the environment and on man. The promotion or establishment of a

vegetative cover on disturbed lands is often included in the reclamation process.

Commonly accepted thinking of land reclamationists from a wide variety of biological disciplines has been that once an herbaceous cover was established on a tailings area, classical plant succession processes would naturally follow to include the invasion and colonization of the tailings by a variety of shrubs and trees representative of the forest cover in the region. Certainly, during the period 1970 to the early 1980's, such thinking was supported by field observations from a variety of tailings disposal areas which had been revegetated including copper, lead-zinc and gold tailings, as well as uranium tailings. However, as many of these revegetated tailings areas become older, there is now evidence that the classical plant succession processes are not in fact occurring. Kalin (1984) quoted by McInnis (1985 - page 32) makes the statement that "stand development differs much from that observed in normal forests". Although no formal studies have been conducted, only visual observations, such a pattern could appear to be true for revegetated tailings disposal areas in the Sudbury, Noranda and Red Lake mining districts of Canada (Watkin, 1985, personal communication).

Although not comparable in terms of climate and type of climax vegetation, certain theoretical aspects of plant community succession and the factors which could possibly affect the form of the succession have been reviewed and investigated by Biondini, Bonham and Redente (1985) for oil shale revegetation in northwestern Colorado. Introduced species used in reclamation have usually been selected for agronomic characteristics such as rapid establishment, high production and favorable response to fertilizer. The use of some cultural practices (e.g. fertilization) can result in an initial competitive advantage to certain groups of these plants that could lead to competitive exclusion of other species and could permanently affect the successional process. Evidence indicating that anticipated classical patterns of plant succession may not, after all, occur on revegetated tailings areas is very far from being decisive, but certain trends are becoming apparent which could cause a re-evaluation of current thinking about the form of final vegetative cover on uranium tailings.

Given the current status of reclamation knowledge for sulphide and non-sulphide uranium tailings, presently designed revegetation programs are based on achieving pragmatic short term solutions for surface erosion control. Insufficient information exists to design a revegetation program encompassing the ideals expressed above. Further, the considered long-term form and stability of the short-term solution must remain largely conjectural. At this stage a precise determination of long-term patterns of development and overall stability is not possible.

Procedures for designing revegetation programs have been discussed by numerous authors (e.g. Hackett, 1977; Downs and Stocks, 1977; Marshall, 1982; Watkin and Watkin, 1982). In general, three major design approaches can be considered.

1. Direct seeding of tailings with agronomic seed mixtures following addition of a soil amendment (e.g. agricultural limestone, organic waste, acidifying chemicals) and fertilizer.

2. Seeding and/or planting of native or indigenous species having a high tolerance to adverse conditions identified as present on the tailings.

3. Isolation of adverse tailings conditions by covering with one or more capping materials (e.g. topsoil, overburden, rock waste, bentonite) and seeding thereon with native, indigenous or agronomic species.

In practice, the three approaches are not mutually exclusive and two or even three approaches may be applied at a particular site depending upon the outcome of initial site investigations and subsequent revegetation plan development. No one method should be advocated to the exclusion of the others. Successful revegetation is dependent upon a flexible and open minded approach in devising revegetation programs.

Prior to devising a revegetation plan though, a number of general characteristics should be assessed at a site. These may be classified into five main groups (Table IV.1-1). It is not considered essential that hard data be obtained for each and every characteristic listed within the five main groups. Considerable laboratory analysis would be required, especially if standard commercial laboratory procedures were undertaken. The interpretation of tailings chemical analysis, which have been obtained using standard agricultural soil analysis techniques is not well understood at present. Attempts to interpret such data in a precise manner can lead to misleading conclusions about the revegetation potential of tailings samples. Several mining companies have conducted investigations to correlate physical and chemical tailings characteristics with revegetation potential of tailings obtained in controlled environment studies. None were successful (Watkin and Watkin, 1982).

For example, under the auspices of the Noranda Mines (Horne Division)-University of Guelph research program "Reclamation of Mine and Industrial Wastes", an attempt was made to correlate such factors as mineralogical analysis of iron sulphide content and form, other mineral constituents, X-ray analysis of heavy and light mineral fractions, X-ray analysis of water soluble constituents, chemical analysis of water soluble constituents, acidity of tailings and standard agricultural soil test analyses of a wide range of oxidized and non-oxidized tailings, with plant growth performance on such tailings. No definite correlation was found between the above factors and plant growth potential. Similar conclusions were drawn from a parallel investigation of various factors undertaken jointly by Rio Algom and Canada Energy Mines and Resources (D. Murray - personal communication).

From a particular viewpoint it is unfortunate that various investigations into the relationship between physical and chemical characteristics of coal mine spoils in the eastern United States and the revegetation potential of those spoils has resulted in the development of a number of standard analytical procedures to aid in reclamation planning. There has been a strong tendency to extrapolate the findings of those investigations for use

TABLE IV.1-1

PRINCIPAL FACTORS TO BE CONSIDERED IN REVEGETATION PROGRAM DEVELOPMENT

| | | | |
|---|---|---|---|
| A. | GENERAL ENVIRONMENT | | |
| | 1. Aspect | | |
| | 2. Prevailing Winds: | Spring, Summer, Fall, Winter | |
| | 3. Precipitation: | Total<br>As Snowfall<br>As Rainfall<br>Monthly Distribution of Total | |
| | 4. Solar Radiation: | Heat Units Received<br>Frost Free Days<br>Length of Growing Season (days above 28°F)<br>Mean Monthly Minimum and Maximum Temperature. | |
| B. | TAILINGS CHARACTERISTICS (PHYSICAL) | | |
| | 1. Texture - Structure - Cementation | | |
| | 2. Density - Compaction | | |
| | 3. Particle Size: | Potential for wind erosion<br>Potential for water erosion<br>Potential for seedbed preparation | |
| | 4. Infiltration Characteristics | | |
| | 5. Water Holding Capacity: | Drought-Impeded Drainage | |
| | 6. Frost Heave | | |
| | 7. Surface Temperature (Colour) | | |
| | 8. Physical Stability: | Potential Diversion Structures | |
| | 9. Available Rooting Depth | | |

TABLE IV.1-1 (continued)

| | | |
|---|---|---|
| C. | TAILINGS CHARACTERISTICS (CHEMICAL) | |
| | 1. Pyritic or non-pyritic | |
| | 2. pH (Acid, Neutral or Alkaline) | |
| | 3. Total Salts (Electrical Conductivity) | |
| | 4. Macronutrient Status | |
| | 5. Phosphorous Fixation Capacity | |
| | 6. Potential Trace Metal Toxicity | |
| D. | SIDE SLOPE CHARACTERISTICS | |
| | 1. Slope Angles, Length and Height | |
| | 2. Slope Surface Uniformity: | Coarse/Medium/Fine-Textured<br>Cemented<br>Degree of Erosion<br>Admixture with Other Materials |
| | 3. Slope Exposure: | Aspect<br>Extremely windblown - Not windblown<br>Minimal Snow cover -<br>depth and duration -<br>days per year |
| | 4. Type of Slope Construction: | Spigoted, Cycloned,<br>Constructed |
| E. | REQUIRED END POINT OF REVEGETATION PROGRAM | |
| | 1. Aesthetic Improvement Only | |
| | 2. Quality Control: | Air, Water, Radionuclide |
| | 3. Future Land Use Options: | Forestry-Recreation-<br>Wildlife |
| | 4. Limitations to Developing | Land Use Options:<br>Waste is Hazardous or Toxic<br>Dangerous Structures<br>Surface Instability |

as similar assessment procedures in the reclamation of tailings, both in Canada and the United States.

An example of how such extrapolation could lead to erroneous conclusions was demonstrated by Caruccio (1976). In earlier studies (Caruccio, 1970) it had been demonstrated that the oxidation of pyrite, and consequent development of acid mine drainage, was governed by the form of pyrite present in coal mine spoils. A particular form of pyrite (fine-grained, termed framboidal) was the only reactive form of pyrite while coarser grained pyrites (euhedral) were found to be not reactive. An examination of various massive sulphide tailings in the Noranda region was undertaken by Caruccio at the request of Noranda Mines (Horne Division). Framboidal pyrite was found not to be prevalent in the investigated samples. In one particular tailings sample where framboidal type pyrite was observed, it was concluded that the sample should be a high producer of acid tailings seepage; assuming of course that the reasoning obtained from eastern U.S.A. coal spoil studies could be extrapolated to a hard rock tailings sample with only minimal investigation. In fact, the particular tailings area from which the sample had been obtained had remained unreactive for many years and was not considered a potential source of acid tailings seepage in the Noranda region.

It is studies such as the above and others reported elsewhere (Watkin and Watkin, 1982; Berg, 1978) that have led to the strong caution on not overemphasizing analytical data on tailings chemical composition. It is suggested that where such data are obtained, they should be used only to provide guidelines or directions as to the existence of potential factors which could influence the design and development of a tailings revegetation program.

At Rio Algom's Elliot Lake properties, revegetation by direct seeding of tailings is an established technology (see Section III.2.7). Future revegetation programs on inactive tailings areas should be feasible provided that:

a) Adequate site preparation is undertaken for surface water control of spring runoff and storm precipitation during summer and fall periods.

b) It is recognized that agricultural limestone requirements for amendment of tailings acidity are not uniformly distributed across a tailings surface and that such variability should be assessed and taken into account when devising the actual reclamation program

c) Fertilization programs and seed mixtures should be refined to account for variability in surface tailings water holding capacity i.e. areas of excessively drained tailings versus areas of poorly drained tailings.

The potential for direct seeding of currently active tailings areas upon completion of tailings deposition is unknown. The point in time between which water in the upper surface (0 - 25 cm) has become sufficiently attenuated to permit vegetation establishment but where the onset of pyrite oxidation has not begun or proceeded sufficiently to represent an environment too acidic for plant growth without addition of soil amendments

has not been determined. It is suggested that an investigation of that relationship be the subject of a future research program.

Due to the paucity of availability of clay materials in the Elliot Lake region it is very unlikely that widespread use of clay materials as an overburden cover for currently inactive or future completed tailings impoundments will find widespread application. Should a clay cover be recommended in specific instances, it should be evaluated for its revegetation potential prior to use, particularly fertilizer requirements where agronomic seed mixtures are being seeded.

General experience obtained from mine reclamation and highway construction programs in northwestern Ontario has shown that the glacial till materials of the region have a high revegetation potential. Their successful use as tailings cover materials is dependent upon correct emplacement procedures (i.e. avoiding overcompaction, ensuring adequate fertilizer application and implementation of correct seeding technology).

Use of sand materials from the region should be approached with greater caution as, in general, sand materials have a lesser revegetation potential than glacial tills. This is due in part to their physical characteristics (more easily drained; greater susceptibility to wind erosion) and to chemical characteristics (lower pH, poorer nutrient retention capacity).

Reclamation technology development in the northern Saskatchewan region is considered to be far less advanced than that in the Elliot Lake region. Although various assessments have been undertaken of the potential factors affecting future tailings in northern Saskatchewan (see I.5.1.B) that general body of information has not yet been transformed to the level of sophistication represented by current reclamation technology in the Elliot Lake region.

In considering future reclamation technology development in northern Saskatchewan it is suggested that a definite distinction be made between those tailings areas (e.g. Gunnar, Lorado) which may be classified as wastes from low grade ores and those tailings areas which may be classified as derived from high grade ores (e.g. Key Lake, Cigar Lake). It is probable that different reclamation (including revegetation) options will have to be developed for the two types of waste areas.

Revegetation recommendations arising from environmental assessments of tailings from ores in low grade inactive tailings areas have veered towards the development and direct seeding or planting of locally occurring native plant materials. It is suggested that there are two drawbacks associated with the recommendations. Firstly, the time frame required to evaluate the adaptability of such species to the various tailings environments and the overall efficiency of selected species in providing an acceptable level of cover. Secondly, the problem common to many investigations which have determined that one or more local native species are adopted for the required purposes is that of sufficient availability of seed or vegetative material for subsequent reclamation programs.

By contrast, the evaluation of the suitability of agronomic species for use on tailings sites can be extremely rapid, within 180 days (Watkin and

Watkin, 1982) and seed availability is not a limiting factor for subsequent reclamation programs. Also, it is generally accepted that agronomic species establish much more rapidly than non-agronomic species. Consequently, surface erosion control is more quickly attained.

A drawback to recommending an agronomic-type reclamation program at low grade inactive tailings areas in the northern Saskatchewan region is that of the logistics of implementation. Successful conclusion of such a program is dependent upon careful site surface preparation, precise application and incorporation of fertilizers and precision in seeding techniques. Specific types of reclamation and agricultural equipment are required to meet the required standards of implementation. For the northern Saskatchewan region, on-site mobilization would be costly, and given the relatively small tailings areas involved, represent, it is suggested, a high cost per acre compared to other suggested alternatives.

Where low grade ore, inactive tailings areas are considered of low environmental impact or where the impact is limited to wind erosion, it is recommended that two reclamation options be considered.

1. No reclamation: Natural plant succession processes will occur over time as determined by present and evolving site conditions.

2. Minimal reclamation: Place thin layers (8 cm) of inert rock waste on tailings to control wind erosion; all natural plant succession processes will occur over time.

The reclamation of low grade tailings with higher environmental impacts (e.g. acidity, salinity, trace metal toxicities, more severe wind erosion) than those discussed above may also be considered reclaimable by the development of native species or agronomic seed mixtures based programs. However, the same drawbacks would apply as to the primarily non-impacting tailings areas.

With the understanding that the impact on water quality of acidic or saline seepages from the generation sites concerned would be controlled, at least in the short term, by various control structures, several cover options may be considered for those tailings representing higher environmental impact.

Firstly, the placement of a low permeability cap directly over the tailings on which would be placed a layer of glacial till material. The objective of the low permeability layer would be to reduce infiltration and subsequent contamination of incident precipitation on the tailings site. Upward salts migration would be reduced by the low permeability layer and hence also contamination of the glacial till cap. The capping layer of glacial till material (approximately 60 cm thick) would enable a natural vegetation cover to develop in time with subsequent effect of reducing percolation by evapotranspiration.

The second option that may be considered differs from the first option in that the low permeability cap is replaced by a coarse rock layer, the purpose of which is to prevent the upward salt migration only. The coarse rock layer would be covered with a glacial till, as in the first option, and allowed to naturally revegetate.

The reclamation of tailings from high grade ore is considered, in many ways, a simple scenario for implementing revegetation practices. Because of the need for intensive containment of the wastes, direct seeding of tailings may not be considered an allowable option. Containment may consist of enclosure by, and capping with, locally available overburden or waste rock materials. Of course, if the approved technology at a particular site is that of water cover, then revegetation technology is not applicable.

The surface stabilization of containment overburdens will not differ in principal from that presently practiced in general construction situations. Depending upon the final design configuration of the containment area, surface erosion control will be by vegetation or placement of rip-rap. Where vegetation is the required form of surface erosion control, careful consideration will have to be given to the final uppermost layers of the overburden (i.e. clay, glacial till, sand) avoidance of compaction, overburden nutrient characteristics and selection of appropriate plant species to provide short to midterm surface erosion control until a stable form of natural vegetation has become established.

Extensive study, with respect to the potential of vegetation as a stabilizer on embankment slopes, is warranted. Aspects such as root structure and its effect on erosion control as a soil movement barrier, wind shield effect, etc., are long term stabilizing factors which have not yet been effectively quantified for design purposes.

### IV.1.3 WASTE ROCK COVER/RIPRAP

The design methodologies for the use of riprap for embankment and slope stabilization is discussed in Technical Memorandum III (Section III.2.6), and a detailed consideration of the factors affecting waste rock revegetation is presented in III.2.9.

Waste rock, borrowed or quarried riprap provides an excellent means for long term erosion protection. Unlike vegetation, riprap will remain effective if subjected to flooding, traffic by animals or human activities and is not effected by fires. Thin riprap covers can be combined effectively with vegetation covers.

Even a relatively thin layer (a few centimeters) provides adequate protection from wind and sheet erosion. If the riprap contains a high proportion of fines this will wash or blow out from between the coarser particles leaving behind a surface layer (sometimes referred to as desert pavement) of coarser particles. To prevent gully or flood erosion requires the placement of more substantial depths (a few tens of centimeters) of appropriately designed and sized riprap.

Waste rock and riprap covers have a number of disadvantages when compared with soil covers.

(i) infiltration is increased

(ii) with dirty rock waste and in the absence of a vegetation cover:

- surface evaporation may be increased which will increase the potential for upward salt migration
- the depth of freezing and potential for frost heave is increased

This disadvantage reduces with the use of clean coarse rock.

(iii) relatively poor radon attenuation characteristics.

Waste rock or riprap provides the most cost effective and secure method of stabilizing steeper impoundment slopes where vegetation alone is not effective. Embankment slopes and all concentrated water flow diversion structures may require such cover to ensure long term stability.

Effective use has been made of waste rock cover materials in the close out of the Beaverlodge mine (Eldorado Resources Ltd., 1983) to cover tailings beaches subjected to flooding. This is an excellent example of a combination of riprap and water cover.

The cost of rock waste and riprap covers is largely dependent on the availability of suitable (durable and environmentally clean) waste rock. If suitable waste rock is not available then a local source of riprap must be identified. If coarse gravels are locally available these may be the most economic alternative. Rock can be quarried and crushed but the cost becomes extremely high and limits the economic viability of this material type.

In the Elliot Lake mines, nearly all mine development is done in the ore with the result that only small quantities of environmentally clean rock waste is produced. To construct riprap covers in this region would generally require the development of a riprap quarry.

At the Saskatchewan open pit mine sites, rock waste is more readily available though many of these wastes contain high percentages of fines.

Placement of riprap covers on both embankments and tailings impoundment surfaces poses practical problems in some areas due to the embankment slopes and soft spots with poor trafficability. The latter difficulty can usually be avoided by placing rock cover materials in the winter.

Costs of rock waste and riprap covers will depend on the costing policy of the mine operator, whether or not outside contractors are used and a large number of site specific variables. For the purposes of general comparison the authors estimate that typical costs would be in the range of $3.00 to $4.00 per cubic meter for sites where rock wastes are available in close proximity and where traffic onto the tailings is possible. Costs may increase by $2.00 to $6.00 per cubic meter if a rock quarry has to be established and if preparation work must be done to achieve trafficability on the tailings.

## IV.1.4 SOIL COVER

Soils that may be borrowed from the proximity of the tailings impoundment is the lowest cost source of placed cover materials. A soil cover layer may be placed for any of the following reasons:

(i) to provide a cover layer to phytotoxic tailings (acid tailings for example)

(ii) to provide a better growth medium for vegetative covers

(iii) to shield gamma radiation and reduce radon emanation

(iv) to provide physical isolation of the tailings from animal and human disturbance

(v) as a sacrificial layer that must be eroded before exposure of the tailings

Vegetation growing directly in uranium mill tailings does not act as a control measure for direct radiation of radon emanation from the tailings (DSMA Atcon, 1985; Rumble and Bjugstad, 1986; Moffett and Tellier, 1977). Soil/overburden covers reduce the radon exhalation flux and shield gamma radiation levels (Hanney et al, 1980). Design guidelines for the design of soil covers for radon attenuation are provided in Rodgers et al, 1984. Moisture in the tailings or soils effect the diffusion and emanation of radon in two ways: first, by blocking the pores of the medium and decreasing the porosity; and second, by absorbing radon (Rodgers et al, 1980). The surface tailings layers of Canadian deposits have greater average moisture contents than the corresponding deposits in uranium producing areas of the U.S.A. Thus the measured rates of radon emanation are considerably lower, and correspondingly of less concern. Similarly, soil cover materials can be maintained at higher average moisture contents, rendering them more effective and permitting lesser thicknesses of soil cover to achieve the desired attenuation. Experience with emanation rates at Beaverlodge (Eldorado Resources Ltd. 1983) and the Elliot Lake deposits (Refer TMI section I.5.3) indicates that none or only minimal soil cover thicknesses are required for tailings from Canadian low grade ores.

Where radon reducing covers are required, consideration should be given to the finer grained soils in the vicinity, such as the tills and clays, which are more effective barriers than the more permeable outwash sands.

The need for soil covers to provide physical isolation of the tailings from low grade ore is considered to be less in Canada than in the U.S.A. because of the relative isolation of the tailings deposits, limiting access and exposures, and an apparent lower incidence of burrowing animals and birds.

The need to achieve physical isolation of the tailings from high grade and more environmentally toxic nickel, arsenic ores is apparent.

Successful revegetation, with long term stability, is considered achievable at all Canadian deposit sites. Thus the need for sacrificial soil erosion

layers is considerably less than in the more arid sparsely vegetated areas of some U.S.A. deposits.

The costs of placing soil covers will depend on the costing policy of the mine operator, whether or not outside contractors are used and a large number of site specific variables. For the purposes of general comparison, the authors estimate that typical costs would be in the range of $2.00 to $3.00 per cubic meter of soil cover, if a suitable soil source is available in close proximity and traffic is possible on the tailings. Haulage costs from sources at some distance rapidly increase the costs as do the need for surface preparation of the tailings impoundment. Overall costs could be increased to twice these values at some locations.

IV.I.5 WATER COVER

The combination of abundant surface water and relatively flat terrain of the Canadian shield renders the use of water as a cover a viable and desirable option under the correct circumstances. A stable water cover can effectively provide isolation and prevent surface erosion, radon exhalation and frost action.

If the appropriate hydraulic and geohydraulic conditions exist, or can be established, then extremely low hydraulic gradients can be achieved with commensurate low infiltration into or seepage from the tailings. It appears paradoxical that submergence of a tailings mass in a permeable envelope in water, with water cover, may provide the means to minimize the leaching and seepage of soluble contaminants from the tailings. This potential has been demonstrated to advantage by Geocon 1984, for the Rabbit Lake Pit, Collins Bay tailings disposal area (See Figure I.6.B-4).

The exclusion of oxygen from acid generating pyritic tailings provides an effective measure for the control of acid generation.

The depth of water cover must be sufficient to:

- cover the tailings at all times so that drying out and wind erosion does not occur
- prevent wave action caused by winds to mobilize the tailings
- prevent freezing and ice rafting of the tailings
- prevent substantial intrusion by man and other biota

Depth of cover may be determined by seasonal, annual or long term precipitation and run off fluctuations and must be evaluated in the design. The effectiveness of water cover has been demonstrated in the close out studies for Beaverlodge Mine (Eldorado Resources, 1983), where tailings had been placed partly into a lake system without any initial intent of providing a formally engineered water cover.

A number of potentially contentious issues have not yet been settled by field demonstrations of actual installations. Included amongst these is the potentially long term primary and secondary consolidation, the

potential entrapment of initially frozen low density tailings and the associated long term squeezing out of tailings solutions. Where water covers are achieved through the use of artificial embankment structures, the long term stability of such structures are critical. The reality, severity and possible remedial measures for such concerns will become apparent with additional implementations.

### IV.1.6 OTHER CONTROL TECHNOLOGY

#### IV.1.6.1 Pyrite Oxidation Control

Pyritic material in Elliot Lake area tailings oxidizes chemically at a low but significant rate in the alkaline pH range (from 7 to 10) (Cherry et al 1983; Senes, 1984). With the Elliot Lake tailings the alkalinity added prior to tailings deposition is rapidly lost once the tailings deposition ceases and the pH declines rapidly in the surface zone (Halbert, Scharer and Knapp, 1984). Once the pH drops below the 6 to 7 range, bacterial oxidation of pyrite starts to play a more important role. Murray (1980) and Murray and Willett, (1982), however, found that "fresh" tailings placed in field lysimeters (and then subjected to various cover treatments - bare, vegetated and several physical covers) did not show acid generation symptoms in the time frame expected from previous experience of Elliot Lake tailings.

Two recent studies (Halbert, Scharer and Knapp, 1984; Hester and Associates, 1984) have stated that a vegetative cover established directly into uranium tailings at Elliot Lake has not been shown to measurably reduce the rate of pyrite oxidation or acid generation in those tailings. While such a conclusion may eventually prove to be correct, the present grounds upon which the conclusion has been drawn are questionable. A discussion on the potential for pyrite oxidation control by a vegetative cover is discussed in Appendix IV.1.1. It is concluded that a vegetative cover, provided it is established early, prior to appreciable acid generation, may significantly assist in the control of acid generation.

The prevention or control of the oxidation of iron sulphides which occur in many hard rock and coal mining wastes has long been a desired waste management objective. An extensive review of past, current and potential preventative control technologies applicable to uranium mill tailings disposal in the Elliot Lake region was undertaken by Hester and Associates (1984). A similar type of review for uranium tailings in general has also been repeated by Sherwood and Serne (1983). The former review concluded that there are many methods for reducing the oxidation of pyrite in pyritic uranium tailings. Pyritic uranium tailings in the Elliot Lake region are considered unique in that the sulphide portion can be reduced an order of magnitude by flotation. Mines treating massive sulphide ore bodies do not have that option. Elliot Lake region tailings also differ from other hard rock tailings in having no natural buffering material; it is removed by a hot strong acid leach during ore processing. One of the recommendations arising from the review was that bacteriacide, phosphates and limestone all be studied as further aids to reducing the rate of pyrite oxidation in Elliot Lake region tailings. The discussion that follows herein is primarily orientated towards re-emphasizing the potential for phosphates in preventing the oxidation of pyrite in uranium mill tailings. It is noted

that phosphate is very slightly soluble (Weast, 1985) and thus the long term effectiveness is questionable. In addition, another chemical grouping, silicates, which were not considered by Hester and Associates, (1984) are also discussed as potential control technology.

Six general categories of possible treatments to prevent or control pyrite oxidation were presented and reviewed by Hester and Associates (1984) (Table IV.1-2). Following the review of possible treatments, nine possible practical approaches were selected for further detailed assessment. They were:

1. Use of muskeg as an organic based cover on tailings which would reduce the concentration of oxygen entering a tailings mass.

2. Flotation of pyrite from the tailings and subsequent disposal (possibly underground) of the pyrite concentrate.

3. Deep water disposal of tailings.

4. Limestone addition to supress pyrite oxidation and bacterial activity.

5. Phosphate rock additions to suppress pyrite oxidation.

6. Sodium lauryl sulphate applications to suppress bacterial activity.

7. Flotation plus pressure leaching.

8. Tailings flotation and acid production.

9. Use of an impervious membrane plus (overburden) cover.

The advantages and disadvantages of each of the nine approaches were summarized and the summary is repeated here.

Of the nine approaches, three refer to flotation. These three define differing ways of disposing of the flotation concentrate: viz - by burial, by pressure leaching with special disposal of the residue, or by roasting for acid manufacture. In all cases the tailings from the flotation circuit are still expected to contain enough sulphide to cause acid generation. Flotation does not stop acid generation, but because it substantially reduces the sulphide quantity present in the tailings at the surface of the basin it should make control easier.

The use of sodium lauryl sulphate can only be considered a short term expedient to get an existing basin which has turned acid under control - to reduce the oxidation rate substantially until some other control technique can be put into place.

Limestone can be considered as a potentially less expensive substitute for lime as it is currently used. It can also be considered as a long term delaying tactic which can reduce the rate of oxidation by maintaining a relatively high pH and preventing bacterial catalysis of pyrite oxidation. Combined with flotation, it seems possible the oxidation rate would be

TABLE IV.1-2

A SUMMARY OF POSSIBLE TREATMENTS TO PREVENT OR CONTROL PYRITE OXIDATION AND ACID TAILINGS SEEPAGE IN URANIUM TAILINGS

| | |
|---|---|
| 1. | Continuous "Artificial" cover. Cover the tailings with some man made material to exclude water and air. |
| 2. | Continuous "Natural" cover. Cover the tailings with naturally occurring material to prevent air entering. |
| 3. | Continuous "Vegetative" cover. Use vegetation in some manner to prevent pyrite oxidation. |
| 4. | "Vegetative" Area. Allow oxidation to proceed naturally, but use vegetation to dampen the impact of acid-runoff on streams. |
| 5. | Modified Process - Add-ons. Consider approaches which can be employed after the current milling process to prevent acid generation from the tailings. |
| 6. | New Milling Processes. Examine the effects of suggested processing changes on the oxidation of pyrite in the final tailings. |

Source: Hester and Associates, 1984.

acceptably low for decades and perhaps centuries. But the potential pyrite oxidation possibility will still remain.

Apatite - phosphate rock - has the potential for control of acid generation and radionuclide emission. Insufficient study has been done on this approach. Potentially it may be more effective than limestone. It appears to be a method requiring considerably more research.

The three remaining methods are approaches for greatly reducing the amount of oxygen which will come in contact with the pyrite. The synthetic membrane approach would be expensive. Some other impermeable barrier above the tailings and below a cover layer might be effective. Movement and screening of material to provide a cover layer would be a large project, and the stripping of the soil in the vicinity of the tailings could cause substantial negative environmental impact. At coal mines in the U.S.A. where such approaches have been tried, the cover material appears to have been overburden which was moved initially.

Muskeg can only be effective in certain topographically suitable areas. It seems to rely primarily on maintenance of a water layer close to or at the tailings surface, and to fixation of oxygen at a layer above the water level. Care must be taken to maintain the bog for the long term.

Deeper water disposal appears to be a long term, maintenance free solution to reduce pyrite oxidation to negligible rates. For the "active" operations, it appears that most of the currently produced tailings could be treated by this method. The proposed technique does assume an ongoing active surface basin which will require some other treatment. The application of the method to an inactive tailings site has not been addressed. It would require reworking those inactive tailings, which is not considered a "practical" approach.

The use of specific chemicals to inhibit the oxidation of pyrite (or other iron sulphides) is a particularly attractive concept. Unlike the other technologies described by Hester and Associates (1984) chemical inhibition can be considered a direct-at-source technology (Deep water disposal of tailings can be considered a possible exception). Whether the chemicals are phosphatic or silicate in origin (as discussed later) control occurs directly at the site of pyrite oxidation, namely the reaction surface of the pyrite particle; and, as has been suggested by Stiller (1983) and Nibgen and Weatherman (1979) an iron phosphate or silicate envelope is formed around the pyrite particle thus inhibiting further oxidation on the particle surface.

Those technologies which attempt to exclude oxygen from the pyritic tailings atmosphere do not in themselves inhibit or prevent the oxidation process at source, the pyrite particle surface. Similarly limestone does not directly inhibit the oxidation reaction but only acts as a neutralizing agent for the acidity produced by the reaction. The effect of limestone as a control on oxidation has a further indirect effect in the sense that it inhibits or prevents the onset of bacterially catalyzed oxidation by controlling the acidity above pH 4.5. Hence any oxidation is significantly impaired or terminated. Sodium lauryl sulphate has no influence on the retardation of the initial pyrite oxidation process.

Consideration of the evolution of the geochemistry of pore water in tailings containing iron sulphate (IV.3.4) would indicate that a chemical control technology could be imposed at any time period (0 to 20 years) during the process controlled stage of evolution and prior to the sulphide oxidation phase that occurs when tailings remain unsaturated. There is insufficient information available to make detailed suggestions as to the time of addition. Indeed, the more-encompassing question of how effective chemical additions actually are must first be resolved.

A summary of chemical treatment processes by phosphate and various silicates is provided in Appendix IV.1.2. At this stage of understanding, it is not possible to conclude that the use of either phosphate or silicate chemicals will provide a means of permanently preventing iron sulphide oxidation in mill tailings.

Currently, the use of chemicals as a control technology is considered limited to the treatment of new tailings only and not as a control technology for already deposited tailings where the evolutionary geochemistry of pore water has entered the sulphide oxidation phase. Practical considerations of treating large volumes of tailings to depth underly that suggestion.

Although considerable emphasis has been placed on the use of chemicals as a pyrite oxidation control technology the authors wish to stress that it is unlikely that any one technology will be all encompassing in its effectiveness. The development of effective control systems is still in its relative infancy. It is most probable that as information is obtained on the various technologies that a multiple system of control technologies will be found to be most effective and acceptable by industry, government and public. For example, a suggested future control scenario could consist of 1) flotation or other in-mill removal of most pyrite, 2) chemical treatment of pyritic tailings prior to deposition, 3) direct vegetation or relatively thin overburden/rock waste emplacement followed by vegetation and 4) a seepage control system (bog system) following the concepts proposed by Kalin (see Hester and Associates, 1984). Further research will be required to advance the above scenario (or any others) from the conjectural phase to one of practical implementation.

### IV.1.6.2 Surface Preparation

Much can be done, prior to placing a cover, to prepare the tailings surface in a manner which promotes good drainage (necessary to limit infiltration and prevent flooding of vegetation) and reduce erosive forces.

A uniformly graded but gently sloping tailings surface enables uniform and good surface drainage with minimal erosion. Such a uniform surface can be achieved by appropriate tailings discharge location in the final years of the impoundment life, by reshaping the tailings surface using conventional earth moving or dredging methods or by placing a cover to variable depths. The cost of achieving the uniform surface usually increases in the order of the options mentioned.

Parts of the tailings mass will be only partially consolidated at the time of reclamation and all the tailings will consolidate further under the weight of cover layers and if there is a reduction of the level of the phreatic surface in the impoundment with time. Consolidation results in settlement of the tailings surface. The variability in the tailings properties and depth of tailings results in differential settlements which distort the uniformly sloping reclamation surface. Where sufficient settlement occurs, such as over areas of thick tailings slimes, depressions may develop in time. If these depressions pond water, then localized flooding and failure of the vegetative cover will occur and infiltration is increased. Seasonal ponding may give rise to wind erosion of uncovered tailings. Methods for the estimation of consolidation settlement in tailings are described by Nelson et al, 1983.

A number of alternative methods may be considered to accelerate the consolidation of tailings prior to surface contouring. These include, dewatering, preloading, blast induced consolidation, dynamic compactors, vibratory compactors, wick drains and compaction piles. Of these, only dewatering is considered to be technically and economically viable in the time frame of interest. Dewatering, to be effective, should be provided for at the time of initial design and construction. Examples of designs which provide for dewatering are the tailings disposal facilities at Key Lake (Knight and Piesold Ltd., 1981) and Rabbit Lake Pit (Geocon Inc., 1984). The use of wick drains would generally be technically applicable but the cost of implementation would generally limit its economic viability to only the most critical portions of the tailings impoundment (such as the slow draining slimes zones).

Accelerated drainage is not possible if portions of the tailings mass is frozen. As these masses thaw and drainage occurs, surface depressions may develop. The incorporation of frozen masses is most likely where (i) dewatered tailings are placed in a "dry" disposal area and (ii) where the rates of rise in a wet disposal area is large (greater than 3 m per year). The effect of frost heaving and permafrost development is also to distort the cover slope. Freeze/thaw controls such as a good vegetative cover, water cover or soil cover reduce the potential for frost heave.

The prevention of biotic intrusion (roots and burrowing animals) is not viewed as a concern for tailings from Canadian low grade uranium tailings deposits. For tailings from high grade nickel arsenic ores it may be of greater concern. The need for barrier layers or other control measures must be evaluated at the time of surface preparation. Dense rigid layers may limit root penetration and large gravel riprap in dense layers may frustrate animal burrowing.

Surface preparation and cover placement requires access onto the tailings impoundment. Trafficability of such surfaces may be difficult in poorly drained areas where fines or slimes accumulations exist. Preparation measures that can be achieved during the winter period, when freezing permits access, do not pose a problem. Where access is required during thawed periods it will be necessary to improve trafficability by installing drainage or a more competent trafficable layer (in winter, if necessary).

IV.1.6.3 Infiltration Control

Infiltration control is of primary importance for all uranium tailings impoundments since water entering the tailings by infiltration must escape from the tailings area as contaminated seepage.

The single most important factor effecting long term infiltration is surface drainage. Where the surface runoff is rapid, the period and pressure heads effective for infiltration are minimized. The second most important factor is the water balance in the surficial layers as a consequence of infiltration, moisture retention and evapotranspiration through plants. Infiltration must be sufficient to create soil moisture conditions which support the vegetative cover required for erosion control. The vegetative cover in turn removes a percentage of the surface infiltration reducing the net infiltration passing down into the tailings mass.

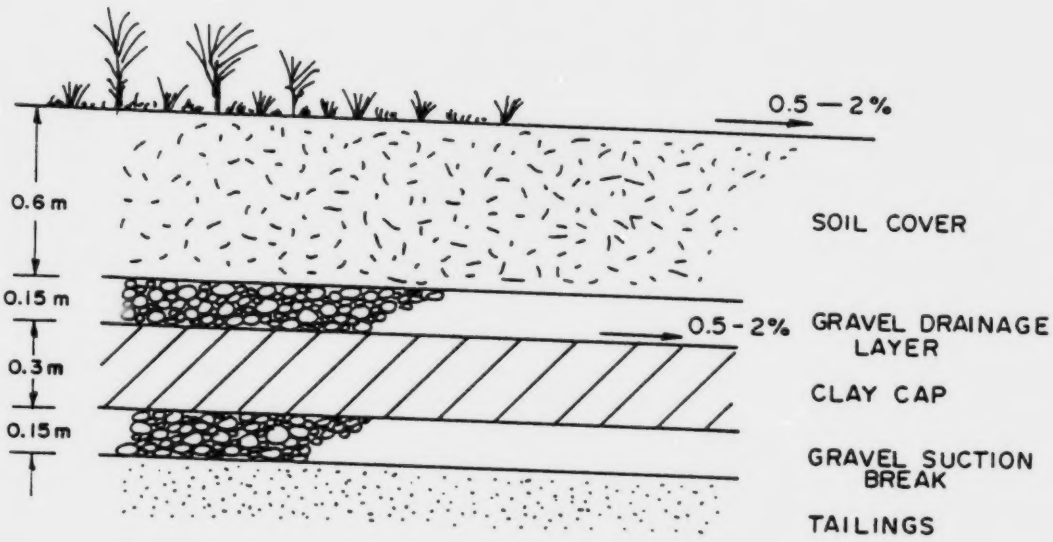
If the above two factors do not limit infiltration to the desired limits then other engineered controls are required. A low permeability cap, constructed of clay or sand and bentonite mixtures, may be installed to impede the downward migration of infiltrating water.

If caps are effective, then in periods of high precipitation the soil above the cap may become water logged. This could result in loss of or change in the vegetation type. The mounding of the water table on a soil covered cap results from the low rate of horizontal drainage on the gently sloping cap. Where water mounds on the cap, high vertical hydraulic gradients develop through the cap. This gradient may be increased as a result of capillary suction in the tailings below the cap. The result is rapid seepage through the cap and in particular through any breaks in the cap. Such breaks could develop as a result of:

- root action
- settlement of the tailings resulting in cracking of the cap
- drying out and shrinkage of the cap materials
- frost action

All of the mechanisms will be active during the period of concern and represent modes of likely failure of the cap. Root action and frost action are considered potentially much more severe modes of cap failure in Canada than in the uranium producing areas of the U.S.A.

To prevent mounding on the cap and suction pressures under the cap, coarse gravel layers can be installed. An illustration of such a cap design is shown in Figure IV.1-2. The long term stability of the upper gravel drainage layer is questionable since root penetration is expected to result in fairly rapid accumulation of organic matter in this layer with associated losses of permeability.




EXAMPLE OF COVER SYSTEM INCLUDING A CLAY CAP WITH GRAVEL DRAINAGE LAYER AND GRAVEL SUCTION BREAKER.

FIGURE IV.1-2

IV.1.6.4 Salt Migration Barriers

One of the least expensive and long term effective barriers to upward salt migration is the establishment of healthy vegetative growth. Upward migration is reduced as a result of:

- surface shading by vegetable matter cover which reduces surface drying and upward capillary gradients,
- promoting surface infiltration and downward gradients at the soil surface,
- removing water in the root zone preventing upward migration, and
- lowering the phreatic surface and zone of salt deposition

Should vegetation be an inadequate salt migration inhibitor then a physical barrier is required. A coarse layer of gravel at depth below the surface acts as a suction breaker preventing the transmission of capillary tension that induces upward flow. Long term concerns regarding such coarse layers are the potential for infilling of the pore spaces due to seepage erosion, biotic activity or salt accumulations.

The applicability of salt migration barriers has been reviewed in section III.6.8.

## IV.2.0 EXTREME EVENTS

### IV.2.1 CLIMATIC CHANGE

Because of the long period of interest, the likelihood of extreme events occurring is proportionately large. The probability of occurrence of fires, floods, tornados or other extreme events, for which there is a record of smaller events, can be determined based on the probability frequency relationships that can be developed for the historical record of events. In Canada, this record is relatively short, generally not more than a few tens of years, and the extrapolation to events that have a probability of occurrence in the very long term of 1000 to 2000 years may be of questionable accuracy. Nevertheless, the methodology is relatively well defined and as the period of record increases, so will our ability to more accurately determine the probability of occurrence of extreme events.

The period of record applies to a period in which a particular climate applied. However, the earths climate is not fixed. Evidence suggests (McInnis 1985) that climatic cycles occur regularly, varying from relatively minor 30 year cycles to major glacial and interglacial cycles of tens to hundreds of thousands of years.

The weather of Canada in several years, or its climate a few centuries from now is unknown (Hare and Thomas, 1974). Thus the record from which the projections of extreme events are made may not be representative of the climatic conditions which may cause them over the next 1000 to 2000 years.

While it is questionable whether man has altered world climate to date, the potential for material alteration increases and this influence may rival or overrule natural climatic changes early in the twenty-first century or sooner (Hare and Thomas, 1974).

Substantial climatic changes can cause extreme events of which there is no recent record in the Canadian uranium tailings areas, such as glaciation, extreme drought or high precipitation periods. Even relatively small changes, such as a temperature change of 2 to 3°C, could have large consequences, such as the potential for permafrost and frost heave, in the Canadian uranium tailings deposits.

Much of the work summarized in this section is taken from McInnis (1985) in which a literature review of long term natural events was undertaken for NUTP.

#### Glaciation

Some general characteristics of climate in the past suggest that an ice age may be due (Kilborn and Beak, 1979). The probability of a transition in the next 100 years to the type of climate leading to an ice age is quoted by Pittock et al, (1978) as being less than one percent. The probability of onset within the next 1000 years of glacial climate associated with the 100,000 year glacial-interglacial cycle is estimated by Lamb (1977) to be about two percent. Given the relatively low probabilities of occurrence as well as the time period required for substantial changes to occur it is

concluded that glaciation is not a significant factor effecting stability over the period of interest.

Greenhouse Effect

An increase in the atmospheric gases increases the efficiency of the atmosphere in trapping radiation from the earth's surface and results in a warming or "greenhouse" effect. The rise of carbon dioxide concentration in the atmosphere is unmistakable (Hare, 1981) with a 25 percent increase currently over that at the beginning of the industrial revolution. A doubling is expected in the next 100 years.

The degree of future warming is debatable, however many studies suggest a doubling of atmospheric carbon dioxide would result in mean global temperature rises of 2.5°C. Since recorded data of the past century indicate that so far, no temperature rise due to carbon dioxide has occurred (Hare, 1981 and Ellsaesser, 1985), predictions should be treated with skepticism.

Two models (Bruce and Hengeveld, 1985 and Parry and Carter, 1984) predict some effects in Canada. They conclude that the temperature rise will be about 2.5° and 2.5° to 5° for the Saskatchewan and Ontario tailings site areas respectively. Natural vegetation of northern Saskatchewan will change from moist boreal forest to cool temperature steppe while that at Elliot Lake will remain cool temperature forest.

In view of the uncertainty of future changes, evaluations of long term stability should be based on the current record with the understanding that greater fluctuations in the range of possible values will become increasingly likely in the long term.

Climatic Cycles

Associated with the short duration climatic cycles there will be periods, for example, which are both wetter and dryer than that measured in the period of record. Shorter periods (of a few years) which are significantly wetter (wet periods) or dryer (droughts) will occur. These periods will have a major impact on such aspects as vegetational survival and the height of the phreatic surface in the tailings impoundments. Average temperature variations can be expected to result in periods of aggradation and degradation of frost, a major potential disruptive force in Canada. Since one is unable to predict such changes they can only be allowed for in a subjective or parametric way in the long term stability evaluations.

IV.2.2 HIGH PRECIPITATION

The methodology for flood estimation has been presented in Section III.2.1.

There is a 63 percent chance that a structure designed for the 100-year return period flood will have its capacity exceeded in 100 years. At a 95 percent confidence level that the capacity of a structure will not be exceeded in 100 years, it must be designed for the 1950-year return period flood (Bruce, 1957). These two probabilities show how significantly the return period of a structure's design flood must increase if the structure

is to be reasonably safe for as short a time as one century. Table IV.2-1 lists more probabilities of X-year floods occurring within selected time intervals.

Annual maximum floods in both Ontario and Saskatchewan result from snowmelt, snowmelt and rain, or rain only. Both areas contain many lakes and swampy areas which produce relatively stable river discharge.

None of the tailings sites are located in the flood plain of a river that floods by ice-jamming.

Two types of storms produce the greatest rainfalls in these regions; tropical cyclones and thunderstorms. Estimates of the high precipitation events up to the 100 year 24 hour storm event for the Elliot Lake and Uranium City (Saskatchewan) areas are given in Tables I.2.A-2 and I.2.B-4. There is a maximum flood of which the catchment basin is capable, termed the probable maximum flood (PMF), which is associated with the probable maximum precipitation event (PMP). The PMP for the Elliot Lake area has been estimated at 420 mm in a 12 hour period (Pullen and Davis, 1982, and MacLaren and Golders, 1980) and about 300 mm in northern Saskatchewan (see section I.2.2.B). These probable maximum precipitation events are approximately three times greater than the 100 year 24 hour precipitation events.

It is apparent that in the 100 to 2000 year time period that precipitation and flood events will occur which significantly exceed the typical design values of the 100 to 200 year storm events.

## IV.2.3 HIGH WINDS

Tornadoes, tropical cyclones and low pressure storm systems are sources of high winds.

### Tornadoes

Tornadoes do not occur in northern Saskatchewan. Elliot Lake lies in the zone of average annual tornado frequency of 0.4 to 0.8/10,000 $km^2$, (Newark, 1983). This demonstrates that the Elliot Lake area will be struck by several tornadoes in the 20 to 2000 year period. Though they are the most destructive of all winds, their duration at a site is too short to weaken an impoundment (Kolousek, 1984).

### Tropical Cyclones

There is no record (or probability) of tropical cyclones in northern Saskatchewan.

Out of 350 Atlantic tropical cyclones during a fifty year period only 25 had noticeable effects on weather in southern Ontario, and only eight caused high winds or excessive rain.

The hurricane return period at Elliot Lake is estimated at 100-200 years (Newark, 1985).

TABLE IV.2-1

PERCENT PROBABILITY OF OCCURRENCE OF EXTREME EVENTS WITHIN SELECTED TIME INTERVALS
(Schumm et al, 1982)

| Event Return Period (years) | Time Interval (years) | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 10 | 100 | 1000 | 5000 | 10000 |
| 500 | 0.2 | 2 | 18 | 86.5 | 99.995 | 99.999 |
| 1000 | 0.1 | 1 | 9.5 | 63 | 99.33 | 99.99 |
| 5000 | 0.02 | 0.2 | 2 | 18 | 63 | 86.5 |

TABLE IV.2-2

PEAK HOURLY WINDS OF SELECTED RECURRENCE INTERVALS AT THE TAILINGS SITES
(Canadian Climate Centre, 1985)

| Location | Peak Hourly Winds (km/h, m/s) | | |
|---|---|---|---|
| | 10 years | 30 years | 100 years |
| Bancroft | 68, 18.9 | 76, 21.1 | 85, 23.6 |
| Elliot Lake | 75, 20.8 | 84, 23.3 | 94, 26.1 |
| Gunnar | 83, 23.1 | 92, 25.6 | 101, 28.1 |
| Key Lake | 93, 25.8 | 101, 28.1 | 111, 30.8 |
| Rabbit Lake | 88, 24.4 | 103, 28.6 | 119, 33.1 |
| Uranium City | 86, 23.9 | 95, 26.4 | 103, 28.6 |

Low Pressure Systems

At the Saskatchewan and Ontario sites, damage to tailings impoundments from high winds is normally due to the low pressure storm systems that are a regular part of the weather (McInnis, 1985). In comparison, tropical cyclones pose a small threat.

Low pressure storm systems are most intense in winter. Peak gusts from thunderstorms in both tailings areas lie between 70 and 90 km/h (19.2 and 25 m/s) (McInnis, 1985).

Table IV.2-2 lists the winds of recurrence intervals of 10, 30 and 100 years at some of the tailings sites.

## IV.2.4 EARTHQUAKES

Dynamic loads due to earthquakes may result in the liquefaction of low density saturated tailings or uncompacted saturated portions of granular embankments or embankment foundation materials. In combination with embankment failure, such liquefaction could result in large releases of tailings.

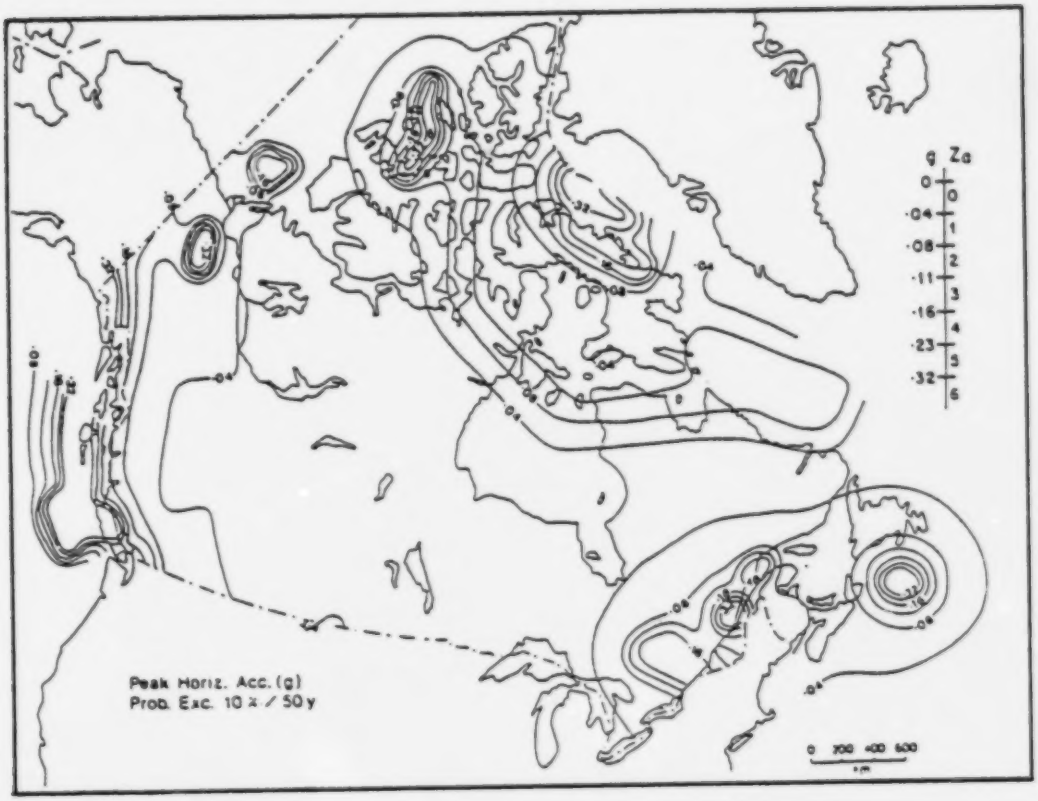
Figures IV.2-1 and IV.2-2 present probability estimates of seismic motion for Canada (Basham P.W, 1983). The Saskatchewan sites are located in a zone of relative seismic stability with a low potential for seismic accelerations at a level likely to induce slope instability or liquefaction.

In the Elliot Lake area seismic activity is low but not negligible. The "Maximum Credible Earthquake" likely to effect the area is of magnitude 7.0 on the Richter Scale (Pullen and Davis, 1982) and is located 225 km from Elliot Lake. It is predicted that the event would cause an intensity IV effect, on the Modified Mercalli Scale, at Elliot Lake, with corresponding peak ground accelerations of 0.065g. Studies by Golder Associates, 1982, and Weston Geophysical Research Inc., 1979, on the potential of liquefaction of tailings indicate that the potential is low, and that the embankments studied would be stable.

Mining induced seismic events have been occurring in the Elliot Lake area as a result of pillar bursting and mine collapse (Hedley et al, 1984). Some of these events have exceeded magnitude 3.5 on the Richter scale.

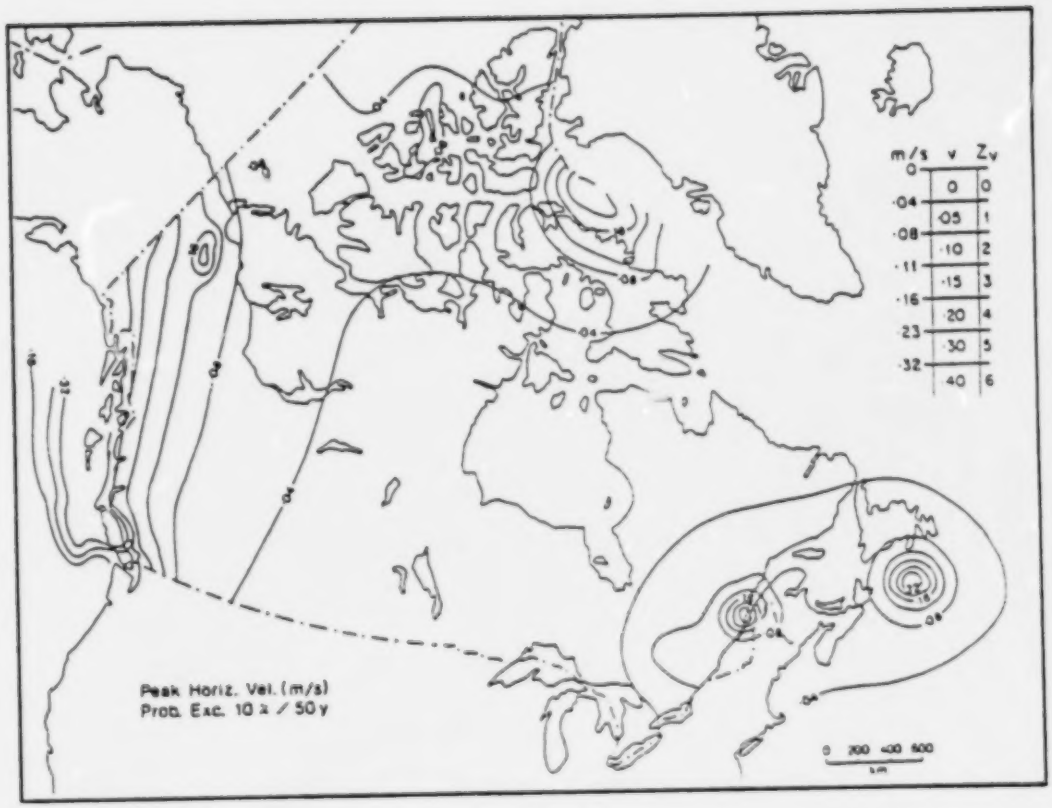
It is considered that there is little likelihood of earthquake induced embankment failure for compacted tailings embankments. Where embankments at Elliot Lake have been constructed of uncompacted tailings sands, and where the phreatic surface rises as a result of drain blockage, the potential for liquefaction should be checked.

There is a significant potential for liquefaction of portions of the tailings within the impoundments which may result in some settling and cracking of cover layers.




PEAK HORIZONTAL ACCELERATION WITH A PROBABILITY OF EXCEEDANCE OF 10% IN 50 YEARS (BASHAM, 1983).

FIGURE IV.2-1




PEAK HORIZONTAL VELOCITY WITH A PROBABILITY OF EXCEEDANCE OF 10% IN 50 YEARS (BASHAM, 1983).

FIGURE IV.2-2

## IV.2.5 FOREST FIRES

All the uranium tailings areas are within natural forest cover areas which have been swept with forest fires at irregular intervals. Past experience is that forest fires are followed by rapid re-generation of the vegetative covers. The greatest risk associated with the temporary loss of cover is the potential for erosion, upward salt migration and frost heaving. Since forest fires may be anticipated on several, if not numerous, occasions in the 100 to 2000 year period of interest, the secondary effects may be severe. These secondary effects are dependent also on other factors and must be evaluated on a site specific basis.

## IV.3.0 EVALUATION OF STABILITY METHODOLOGY FOR COVERS

### IV.3.1 WATER EROSION

Water erosion can occur as:

1) Sheet or interrill erosion: which is the removal of a thin relatively uniform layer of soil particles

2) Rill erosion: which is erosion in numerous small channels that are a few millimeters wide and deep

3) Gully erosion: gullies are rills which cannot be obliterated by normal tillage practices

4) Stream channel erosion: erosion occurs due to the streamflow

5) Landslide erosion: erosion occurs as a mass soil movement due to slope instability

For single storm events the release rates associated with sheet, rill and gully erosion will be small. Erosion due to these mechanisms will occur on tailings impoundment covers and embankments and the adverse impacts of this type of erosion will probably not occur for a number of years. The most suitable methods for predicting these impacts are:

1) Sheet and Rill Erosion

   a) Universal Soil Loss Equation (USLE)
   b) Modified Universal Soil Loss Equation (MUSLE)

2) Gully Erosion

   a) Method of Falk et al. (1985)

Discussions on the application of each of these procedures are presented in this section and IV.4 together with anticipated release estimates for Canadian uranium tailings impoundments.

Stream channel erosion is discussed in Section IV.5. Significant stream channel erosion could occur in a single severe flood event or over a long period due to a number of small events. Numerous methods have been developed for predicting channel erosion or designing stable channel walls. Commonly used methods include:

1) Critical shear stress methods

2) Tractive force methods

Other methods include:

1) Safety Factor Method (1975)

2) Stephenson Method (1979)

Although stream channel erosion is discussed in Section IV.5, stream channel erosion could occur on the cap and toe of tailings impoundments. Also, the methods used to design stable channel walls could be applied to the design of stable covers. Use of the tractive force method for this purpose is illustrated in Appendix IV.3.1.

Landslide erosion is discussed in the section on slope stability. Failure by this mechanism will result in a sudden large displacement of material. However, following failure, movement of this material away from the impoundment will be due to one of the other erosion mechanisms.

Sheet and Rill Erosion

The most commonly used method for predicting erosion is the USLE (Wischmeier and Smith, 1965). The method is described by the equation:

$$A = R\ K\ LS\ C\ P \qquad (3.1)$$

where: A is the soil loss per unit area, R is the rainfall erosion factor, K is the soil erodibility, LS is a dimensionless length slope factor, C is a dimensionless soil cover factor and P is a dimensionless conservation practice factor. A discussion on parameter estimates for Canadian tailings impoundments follows. A detailed account of parameter determination is presented by Barfield et al. (1981) and is summarized in Technical Memorandum III.

In order to make estimates of erosion rates using this method, reliance must be placed on factors developed for USA conditions. While some of the values are directly transferrable and applicable there are some that should be modified to be specific to Ontario and Saskatchewan uranium tailings site conditions.

The rainfall factor,R, is estimated based on the product of rainfall energy times the maximum 30 minute intensity of rainfall ($EI_{30}$), or:

$$R = EI_{30}/100 \qquad (3.2)$$

Average annual values of R can be estimated based on the 2 year, 6 hour rainfall event (Hotes et al., 1973). For SCS Type 1 and 2 rainfall distributions the following relationships can be used:

$$R = 16.6\ P^{2.2} \text{ (TYPE 1)} \qquad (3.3)$$

and

$$R = 27.0\ P^{2.2} \text{ (TYPE 2)} \qquad (3.4)$$

where P is the 2 year, 6 hour rainfall depth in inches. Type 2 rainfall distributions should be used for all Canadian tailings impoundment locations. For Canadian conditions, light rainfall associated with spring thaws could cause significant runoff and erosion, although the the rainfall index is very small. For the Palouse area of Washington, Oregon and Idaho,

McCool et al (1976) suggest that a combined rainfall-runoff index can be given by

$$R = 27P^{2.2} + 1.5\ P_{DM} \qquad (3.5)$$

where $P_{DM}$ is the December to May rainfall in inches.

For regions where Canadian uranium tailings impoundments are located it is anticipated that average annual values of R will range from about 30 to 90. Average storm R values can be estimated from Figure IV.3-1. Storm R values for the 100 year flood will vary from 50 to 200 depending on the location and storm duration. The rainfall erosion index associated with the PMP will probably be 5 to 10 times higher than that for the 100 year flood.

The soil erodibility factor, K, is a function of the soil texture, the organic matter content, soil structure and the soil permeability. Estimates can be made from the nomographs presented in Figures IV.3-2 and IV.3-3. These nomographs will give reasonable estimates of K for soils. However, estimates for tailings materials should be used with caution.

It is anticipated that soil cover materials will have K values of 0.2 to 0.5 and the tailings materials will have erodibility values of 0.4 to 0.8. In some cases cementing and armouring of tailings materials could result in very low K values.

The LS factor can be estimated by the following equation (Wischmeier and Smith, 1965):

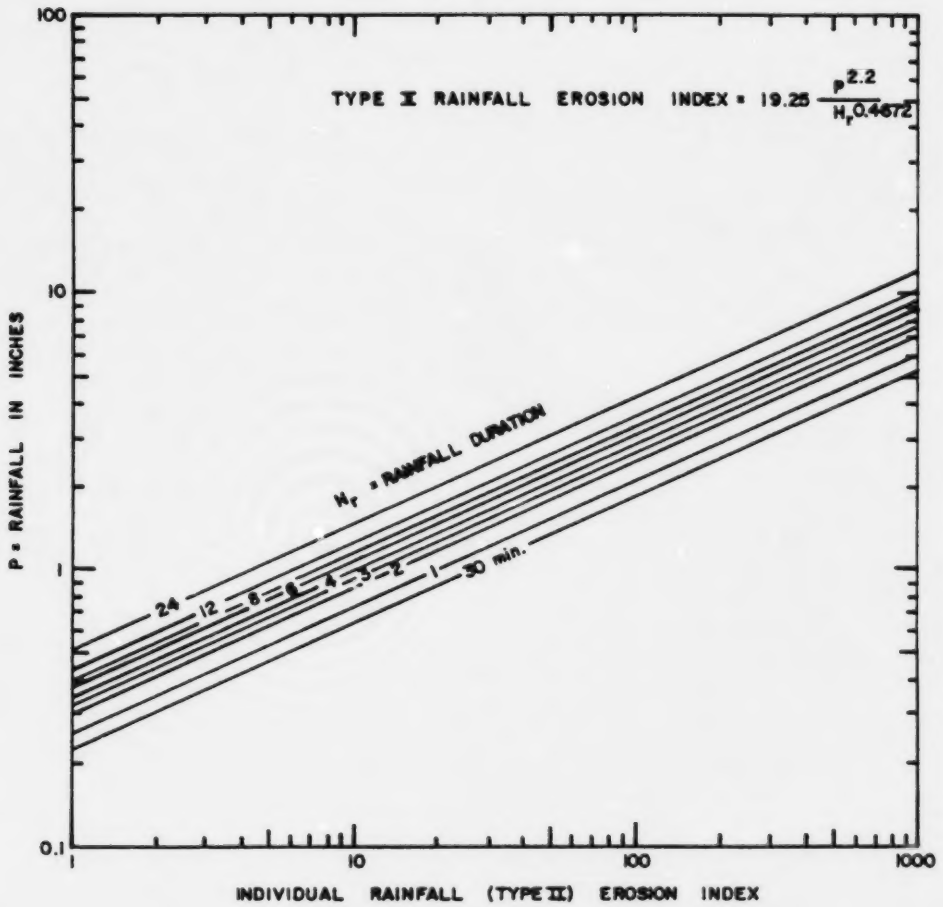
$$LS = 0.151\ [0.014\ L]^m\ [430\ X^2 + 30X + 0.43] \qquad (3.6)$$

where L is the slope length (feet), x is sin A, A is the slope angle, and m is an exponent dependent upon the slope given by:

m = 0.3 (if the slope less than or equal to 3%)
m = 0.4 (if the slope equal to 4%)
m = 0.5 (if the slope greater than or equal to 5%)

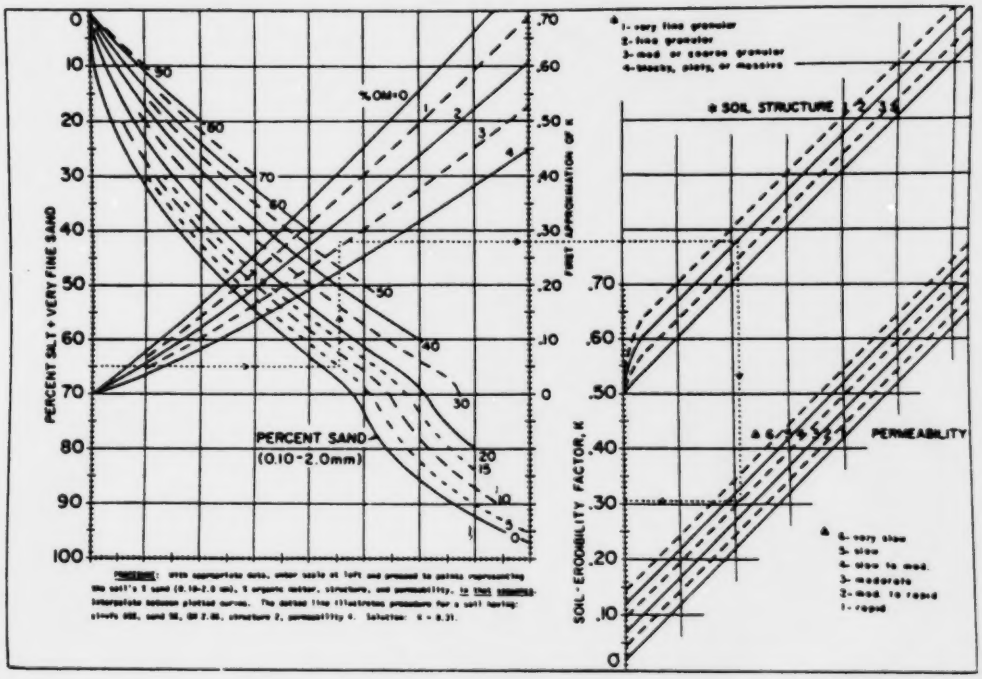
Solutions of this equation are presented in Figure IV.3-4. The dashed lines are projections beyond the range of experimental data. Typically, the LS topographical factor will have values of 0.1 to 1.0 on tailings impoundment caps and values of 5.0 to 50.0 on embankment sideslopes.

The cover factor, C, and the practice factor, P, are combined together into a single CP factor. The CP factor is defined as the ratio of sediment loss from a field with a given cover and conservation practice to that of a field in continuous fallow. Reasonable estimates of CP values which are applicable to Canadian tailings impoundments are presented in Table IV.3-1. It might be anticipated that in the long term CP values will range from 0.02 to 0.2 for all vegetated impoundments.



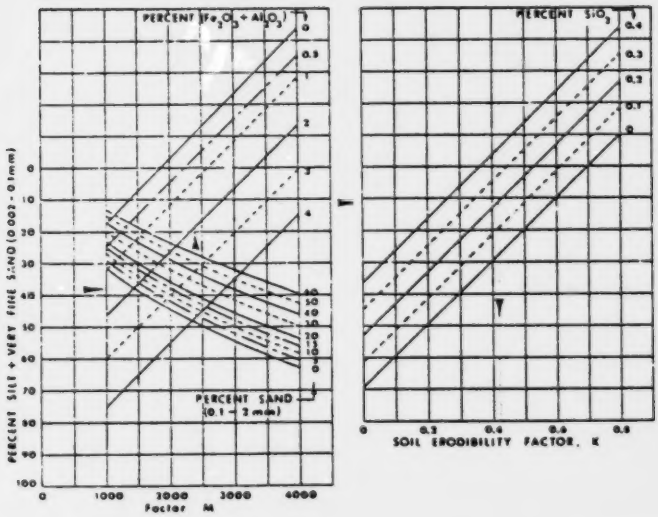

RELATION BETWEEN DEPTHS AND DURATION OF TYPE II RAINFALL AND SINGLE STORM EROSION INDEX (HOTES ET AL., 1973)

FIGURE IV.3-1



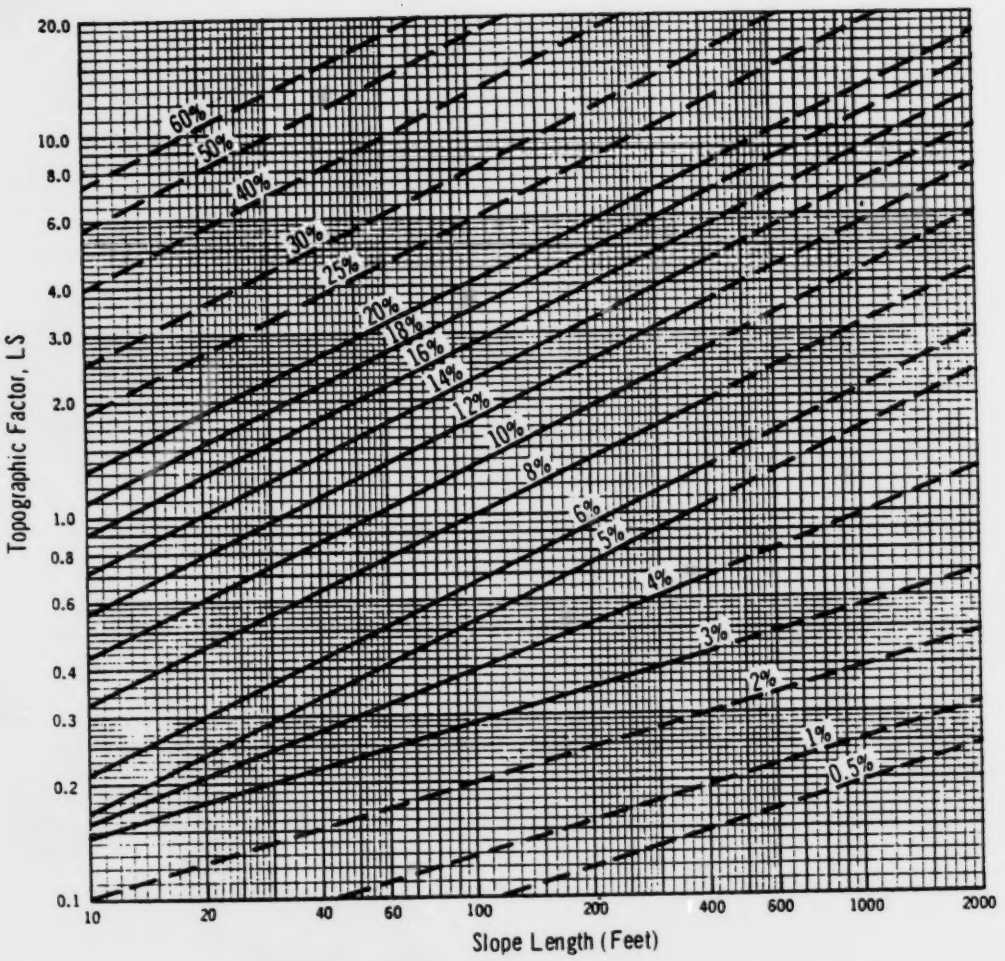

NOMOGRAPH FOR ERODIBILITY FACTOR FOR SURFACE AND LOW CLAY SUBSOILS
(WISCHMEIER ET AL., 1971)

FIGURE IV.3-2




NOMOGRAPH FOR ESTIMATING THE ERODIBILITY FACTOR, K, OF HIGH CLAY SUBSOILS
(ROTH ET AL., 1974)

FIGURE IV.3-3




*The dashed lines represent estimates for slope dimensions beyond the range of lengths and steepnesses for which data are available. The curves were derived by the formula:

$$LS = \left(\frac{\lambda}{72.6}\right)^{m} \left(\frac{430x^2 + 30x + 0.43}{6.613}\right)$$

where $\lambda$ = field slope length in feet and $m = 0.5$ if $s = 5\%$ or greater, 0.4 if $s = 4\%$, and 0.3 if $s = 3\%$ or less; and $x = \sin\theta$. $\theta$ is the angle of slope in degrees.

SLOPE-EFFECT CHART (TOPOGRAPHIC FACTOR, LS)(SCS, 1977)

FIGURE IV.3-4

| Vegetal Canopy | | | Cover that Contacts the Surface | | | | | |
|---|---|---|---|---|---|---|---|---|
| Type and Height of Raised Canopy[2] | Canopy Cover[3] % | Type[4] | Percent Ground Cover 0 | 20 | 40 | 60 | 80 | 95-100 |
| No appreciable canopy | | G | .45 | .20 | .10 | .042 | .013 | .003 |
| | | W | .45 | .24 | .15 | .090 | .043 | .011 |
| Canopy of tall weeds or short brush (0.5 m fall ht.) | 25 | G | .36 | .17 | .09 | .038 | .012 | .003 |
| | | W | .36 | .20 | .13 | .082 | .041 | .011 |
| | 50 | G | .26 | .13 | .07 | .035 | .012 | .003 |
| | | W | .26 | .16 | .11 | .075 | .039 | .011 |
| | 75 | G | .17 | .10 | .06 | .031 | .011 | .003 |
| | | W | .17 | .12 | .09 | .067 | .038 | .011 |
| Appreciable brush or bushes (2 m fall ht.) | 25 | G | .40 | .18 | .09 | .040 | .013 | .003 |
| | | W | .40 | .22 | .14 | .085 | .042 | .011 |
| | 50 | G | .34 | .16 | .085 | .038 | .012 | .003 |
| | | W | .34 | .19 | .13 | .081 | .041 | .011 |
| | 75 | G | .28 | .14 | .08 | .036 | .012 | .003 |
| | | W | .28 | .17 | .12 | .077 | .040 | .011 |
| Trees but no appreciable low brush (4 m fall ht.) | 25 | G | .42 | .19 | .10 | .041 | .013 | .003 |
| | | W | .42 | .23 | .14 | .087 | .042 | .011 |
| | 50 | G | .39 | .18 | .09 | .040 | .013 | .003 |
| | | W | .39 | .21 | .14 | .085 | .042 | .011 |
| | 75 | G | .36 | .17 | .09 | .039 | .012 | .003 |
| | | W | .36 | .20 | .13 | .083 | .041 | .011 |

1. All values shown assume: (1) random distribution of mulch or vegetation, and (2) mulch of appreciable depth where it exists. Idle land refers to land with undisturbed profiles for at least a period of three consecutive years. Also to be used for burned forest land and forest land that has been harvested less than three years ago.
2. Average fall height of waterdrops from canopy to soil surface: m = meters.
3. Portion of total area surface that would be hidden from view by canopy in a vertical projection (a bird's-eye view).
4. G: Cover at surface is grass, grasslike plants, decaying compacted duff or litter at least 2 inches deep.

   W: Cover at surface is mostly broadleaf herbaceous plants (as weeds with little lateral root network near the surface), and/or undecayed residue.
5. Soil Conservation Service (1977).

CP FACTORS FOR PERMANENT PASTURE, RANGELAND, IDLE LAND, AND GRAZED WOODLAND. 1,5

TABLE IV.3-1

Modified Universal Soil Loss Equation (MUSLE)

The modified Universal Soil Loss Equation can be used to determine sediment yields from single storm events. The method is defined by the equation:

$$Y = 11.8(Q_q)^{0.56} K\ LS\ CP \qquad (3.7)$$

where: Y is the single storm sediment yield in tonnes, Q is the storm runoff volume in cubic metres, q is the peak storm discharge in cubic metres per second and K, LS, and CP are the standard USLE terms.

The main advantage of the procedure over the USLE is that site specific estimates (or relative estimates) can be made of sediment yields associated with different flood events. If historical rainfall records are available for the site then the procedure can also be used to make longterm erosion estimates.

The main disadvantage of the procedure is that the coefficient of 11.8 and the exponent of 0.56 were developed from a limited data base in Texas. Ward et al., (1980) note that the exponent might vary from 0.5 to 1.0.

Use of the procedure requires the estimation of the runoff volumes and runoff rates associated with a storm event. As discussed in Technical Memorandum III, numerous methods are available for making these estimations. Commonly used approaches are:

1) empirical equations

2) unit hydrograph techniques

3) time-area method

4) kinematic method

The most commonly used techniques are the empirical Rational method and the SCS empirical unit hydrograph technique. The Rational method is strictly a peak flow procedure and is not suitable for use with the MUSLE sediment yield procedure. SCS concepts have been incorporated into a computer procedure called WASHMO (Ward et al., 1981) which has been modified to permit the determination of sediment yields using MUSLE. Use of the procedure to determine runoff rates and sediment yields from a tailings impoundment side slope is presented in Appendix IV.3.1. Curve number estimates for use with the procedure can be made from the information presented in Table IV.3-2.

Use of the procedure suggests that single event sediment yields from extreme events will be very significant. It might be expected that yields from 100 year storm events will be several times larger than average annual yields and that yields from the PMP could be 100 times average annual yields.

TABLE IV.3-2 RUNOFF CURVE NUMBERS FOR SELECTED AGRICULTURAL, SUBURBAN, AND URBAN LAND USE.
(ANTECEDENT MOISTURE CONDITION II)

| LAND USE DESCRIPTION | | HYDROLOGIC SOIL GROUP | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| Cultivated land[1]: without conservation treatment | | 72 | 81 | 88 | 91 |
| : with conservation treatment | | 62 | 71 | 78 | 81 |
| Pasture or range land: poor condition | | 68 | 79 | 86 | 89 |
| good condition | | 39 | 61 | 74 | 80 |
| Meadow: good condition | | 30 | 58 | 71 | 78 |
| Wood or Forest land: thin stand, poor cover, no mulch | | 45 | 66 | 77 | 83 |
| good cover[2] | | 25 | 55 | 70 | 77 |
| Open Spaces, lawns, parks, golf courses, cemeteries, etc. | | | | | |
| good condition: grass cover on 75% or more of the area | | 39 | 61 | 74 | 80 |
| fair condition: grass cover on 50% to 75% of the area | | 49 | 69 | 79 | 84 |
| Commercial and business areas (85% impervious) | | 89 | 92 | 94 | 95 |
| Industrial districts (72% impervious). | | 81 | 88 | 91 | 93 |
| Residential:[3] | | | | | |
| Average lot size | Average % Impervious[4] | | | | |
| 1/8 acre or less | 65 | 77 | 85 | 90 | 92 |
| 1/4 acre | 38 | 61 | 75 | 83 | 87 |
| 1/3 acre | 30 | 57 | 72 | 81 | 86 |
| 1/2 acre | 25 | 54 | 70 | 80 | 85 |
| 1 acre | 20 | 51 | 68 | 79 | 84 |
| Paved parking lots, roofs, driveways, etc.[5] | | 98 | 98 | 98 | 98 |
| Streets and roads: | | | | | |
| paved with curbs and storm sewers[5] | | 98 | 98 | 98 | 98 |
| gravel | | 76 | 85 | 89 | 91 |
| dirt | | 72 | 82 | 87 | 89 |

[1] For a more detailed description of agricultural land use curve numbers refer to National Engineering Handbook, Section 4, Hydrology, Chapter 9, Aug. 1972.

[2] Good cover is protected from grazing and litter and brush cover soil.

[3] Curve numbers are computed assuming the runoff from the house and driveway is directed towards the street with a minimum of roof water directed to lawns where additional infiltration could occur.

[4] The remaining pervious areas (lawn) are considered to be in good pasture condition for these curve numbers.

[5] In some warmer climates of the country a curve number of 95 may be used.

Gully Erosion

The method developed by Falk et al. (1985) can be used to estimate:

1) the maximum depth of incision

2) the location of the maximum depth of incision

3) the width of the gully at the maximum depth of incision

A summary of the procedure follows. A more detailed description is presented in Falk et al. (1985). It should be noted that although the approach appears promising it has not yet been verified and can only be used for periods of less than 200 years.

Characteristics of the tailings impoundment side slopes are illustrated in Figure III.2-11. Information requirements include:

1) cover material median particle diameter in mm ($D_{50}$) and uniformity coefficient, $C_u$

2) side slope dimensions including the length, L, slope height, H, and the initial gradient, $S_i$

3) historical rainfall records for the site or nearby vicinity

4) design life of the cover

It is also necessary to determine the upstream drainage area to any point on the side slope which may serve as a drainage outlet, and to define the longest potential watercourse that traverses the cover to the toe.

The method suggests that the drainage area be determined by using an empirical equation presented by Mosley (1971)

$$D = 0.909 + 22.418\ S_i \qquad (3.8)$$

where D is the drainage density area per unit length of channel ($ft^2/ft$) and $S_i$ is the design or initial slope of the cover before gullying. The equation is applied to each segment with similar slopes and the total area determined as follows:

$$A_{Total} = D_j L_j + D_{j+1}\ L_{j+1} + \cdots \qquad (3.9)$$

where $L_j$ is the potential watercourse length at a slope of $S_i$ for drainage density $D_j$.

The stable side slope is then determined from the equation:

$$S_s = 41.2\ (1 + D_{50})\ /\ (A\ P) \qquad (3.10)$$

where A is the tributary drainage area in square feet, P is the average annual number of precipitation events greater than or equal to 12 mm (0.5 inches) and $D_{50}$ is the median particle size, in mm, of the slope.

During the period of evaluation, the side slope will be between the initial slope, $S_i$, and the stable slope, $S_s$. The interim or transitional slope, $S_t$, is defined as the slope of the tangent extending from the toe to the deepest point in the gully. The transitional slope is calculated as follows:

$$S_t = S_i e^{-(GS_s t)} \qquad (3.11)$$

where G is a function of the stable slope and t is the design life of the cover. The coefficient G can be estimated from Figure III.2-12. The maximum depth of gully incision, $D_{max}$, is estimated as

$$D_{max} = (LD/L)\ (H-X(S_t + S_s)) \qquad (3.12)$$

where $D_{max}$ is the maximum depth of gully incision, $L_D/L$ is the occurrence of $D_{max}$ from the toe and X is the horizontal distance from the toe to the crest of the slope. The occurrence can be determined from Figure III.2-13.

The approximate gully top width can be estimated as:

$$W_T = 4.936 + 2.923\ LOG\ (D_{max}/C_u) \qquad (3.13)$$

where $W_T$ is the top width at $D_{max}$ and $C_u$ is the uniformity coefficient of the cover material.

Use of the procedure is illustrated in Appendix IV.3.1. Gully formation will be very site specific and will depend to a large degree on the size of the upstream drainage area.

In many locations no gully erosion will occur. Main problem areas will be caps with large upstream drainage areas or long slopes without drainage control. Side slopes of all impoundments will be susceptible to gully erosion. Over periods in excess of 100 years, depths of incision in vegetated side slopes will probably range from less than a metre to more than 10 metres. Although a number of gullies could form on an impoundment it is probable that gully erosion will only affect a small portion of the surface area of an impoundment.

Limitations of the method are:

1) Developed from limited American data

2) Not developed from uranium tailings impoundment data

3) Does not account for variations in vegetative cover

4) Cannot be used for periods greater than 200 years and is based on data from impoundments less than 35 years old

Cover Erosion Release Rates

Release rates will vary from impoundment to impoundment depending on the following factors:

1) Cover material type (soil, tailings, riprap, water)

2) Vegetative cover (bare material, grassed, trees, etc)

3) Climatic conditions at the site (rainfall, frost, etc)

4) Cover geometry (length and slope)

5) Upstream contributing drainage area

6) Drainage and erosion control measures (berms, terraces, diversions, etc)

To make general estimates of probable erosion release rates is therefore difficult and could be misleading. However, to provide an idea of the order of magnitude of these rates a range of anticipated rates over a 100 year period are presented below:

1) Soil or tailings cover: 1 to 10 metres

2) Grass cover: 0.1 to 2.0 metres

3) Grass and tree cover: 0.05 to 1.0 metres

The estimated release rates are for slopes of 0.5% to 10%. Release rates for slopes greater than 10% are presented in Section IV.4. Estimates have not been made for riprap and water covers as release rates for these covers will be insignificant.

In making estimates for bare soil and tailings covers it has been assumed that no vegetation would be established during the life of the cover. In practice this is probably not realistic. For soil covers it is extremely unlikely that measures would not be taken to develop a vegetative cover. However, even if no actions were taken to develop a vegetative cover it is probable that in the long term vegetation would be established naturally. For tailings materials it might be expected that in some locations vegetation would be difficult to establish. However, self-armouring could occur and release rates would reduce with time.

Over a 1000 year period it is probable that the erosion will be 10 times higher. Average annual release rates will probably reduce with time (unless there is a loss of vegetative cover). However, the probability of a severe flood event occurring will increase with time.

Sheet and rill erosion could occur over large portions of a tailings impoundment. Gully erosion will generally only occur in a few localized locations. It should also be noted that gullies will tend to reach some maximum depth of incision and will then tend to widen due to the collapse

of the gully sidewalls. No information is available on the maximum depth of incision of a gully in uranium tailings materials or soil covers. It is anticipated that this maximum depth will be 5 to 10 metres. With time gullies could become very wide and release rates associated with the washing away of loose collapsed material could be a major concern.

IV.3.2 WIND EROSION

Wind erosion losses are a function of soil erodibility, surface roughness, site characteristics, vegetation and climatic conditions. The most commonly used equation is (Chepil and Woodruff, 1963):

$$E = f[I', K', C', L', V] \quad (3.14)$$

where E is the soil loss in tons per acre per year, I' is the soil wind erodibility factor, C' is a local wind erosion climatic factor, K' is the soil surface roughness factor, V is a vegetation factor, and L' is the length of the unshielded distance parallel to the wind.

Soil erodibility by wind is directly related to the percentage of dry, non-erodible soil aggregates that are larger than 0.84 mm in diameter. Values of the erodibility factor I' are presented in Table IV.3-3.

The soil surface roughness factor, K', accounts for the orientation of the vegetative cover and for clod roughness. The K' factor also denotes the resistance to wind erosion by ridges of given heights and spacings compared to a standard ridge-spacing ratio of 1:4. The expression for finding the soil ridge roughness, $K_r$, in inches is:

$$K_r = \text{field ridge height (standard ratio/field ratio)} \quad (3.15)$$

Figure IV.3-5 can be used to determine K' from $K_r$.

The rate of soil loss by wind varies directly as the cube of wind velocity, U, and inversely as the square of the soil surface moisture, M. The soil surface moisture, M, varies directly with the amount of rainfall and inversely as the square of temperature. The Thornthwaite potential evapotranspiration rate (PE) can be used as an index of soil moisture and the wind erosion climatic factor, C', can be estimated from the equation:

$$C' = 34.48 \, [U^3 / PE^2] \quad (3.16)$$

where U is the mean annual wind velocity corrected to a standard height of 10 metres and PE is estimated as:

$$PE = 115 \, (P/T\ 10)^{111} \quad (3.17)$$

where P is the rainfall depth in inches and T is the temperature in degrees Fahrenheit.

Equations 3-16 and 3-17 can be used to make site-specific estimates of C'. However, reasonable estimates can be made based on provincial and national map data. Monthly map information which has been developed for the United States is presented in Appendix IV.3.3. Typical monthly C' values for the

TABLE IV.3-3 SOIL ERODIBILITY I FOR SOILS WITH DIFFERENT PERCENTAGES OF NONERODIBLE FRACTIONS AS DETERMINED BY STANDARD DRY SIEVING[1].

| Dry soil fractions >0.84 mm. (percent) Units → / Tens ↓ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Tons per acre* | *Tons per acre* | *Tons per acre* | *Tons per acre* | *Tons per acre* | *Tons per acre* | *Tons per acre* | *Tons per acre* | *Tons per acre* | *Tons per acre* |
| 0 | ------ | 310 | 250 | 220 | 195 | 180 | 170 | 160 | 150 | 140 |
| 10 | 134 | 131 | 128 | 125 | 121 | 117 | 113 | 109 | 106 | 102 |
| 20 | 98 | 95 | 92 | 90 | 88 | 86 | 83 | 81 | 79 | 76 |
| 30 | 74 | 72 | 71 | 69 | 67 | 65 | 63 | 62 | 60 | 58 |
| 40 | 56 | 54 | 52 | 51 | 50 | 48 | 47 | 45 | 43 | 41 |
| 50 | 38 | 36 | 33 | 31 | 29 | 27 | 25 | 24 | 23 | 22 |
| 60 | 21 | 20 | 19 | 18 | 17 | 16 | 16 | 15 | 14 | 13 |
| 70 | 12 | 11 | 10 | 8 | 7 | 6 | 4 | 3 | 3 | 2 |
| 80 | 2 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ |

[1] For fully crusted soil surface, regardless of soil texture, erodibility *I* is, on the average, about one-sixth of that shown.

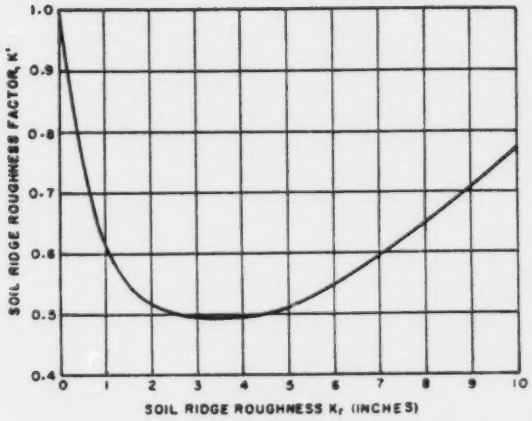



CHART TO DETERMINE SOIL RIDGE ROUGHNESS FACTOR K' FROM SOIL RIDGE ROUGHNESS $K_r$.

FIGURE IV.3-5

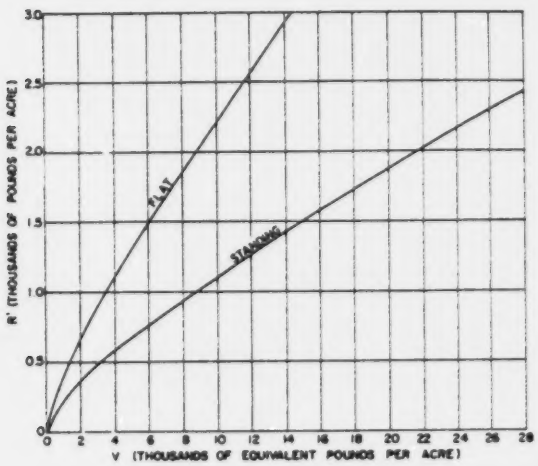



CHART TO DETERMINE V FROM R' OR R' FROM V OF STANDING AND FLAT ANCHORED SMALL GRAIN STUBBLE WITH ANY ROW WIDTH UP TO 10 INCHES, INCLUDING STOVER.

FIGURE IV.3-6

locations of Canadian uranium tailings impoundments will range from 5 to 50 percent.

The field width, L', is the unsheltered distance across a field or strip along the prevailing wind erosion direction. However, soil flow increases proportionately to flow distance until a maximum soil flow is reached. The distance required for soil flow to reach the maximum is the same for any erosive wind and only varies with the soil erodibility of a surface. If a barrier is located on the windward side of a field, the unsheltered field width along the prevailing wind erosion direction is reduced by the distance protected by the barrier. The distance protected by a barrier is equal to 10 times the effective height of the barrier.

The vegetative cover index, V, is used to account for vegetative residue on the surface. It accounts for the quantity of residue, the kind of residue and the orientation of the residue. Values of V can be determined from Figures IV.3-6, IV.3-7 and IV.3-8.

Values of E are determined by using the parameter estimates obtained from the equations, tables and figures discussed earlier and Figures IV.3-9 and IV.3-10. An example problem which illustrates the use of the equation is presented in Appendix IV.3.1.

Wind Erosion Release Rates

Like water erosion it is very difficult to make general estimates of wind erosion release rates. However, to provide an indication of probable release rates for different cover types, a range of estimates for a 100 year period is presented below:

1) Soil or tailings cover: 0.1 to 1.0 metres

2) Grass cover: 0.05 to 0.5 metres

3) Grass and trees: insignificant

It should be noted that only some impoundments and/or parts of some impoundments will be susceptible to wind erosion. On some parts of an impoundment it should be anticipated that wind erosion release rates will be higher than the values reported above.

The range of reported values should not be used to establish design cover thickness requirements. Site-specific evaluations should be made to determine cover thickness requirements to provide protection from wind and water erosion.

## IV.3.3 VEGETATION STABILITY AND BIOLOGICAL PENETRATION

In both northern Saskatchewan and the Elliot Lake region the development of a forest cover on tailings and capping materials similar to that which characterizes each region at present is an oft-quoted objective of proposed reclamation programs. A forest cover is considered most ideal for two major reasons. Forest is the climax vegetative cover for each region and hence is considered to represent the most stable and long-term vegetative

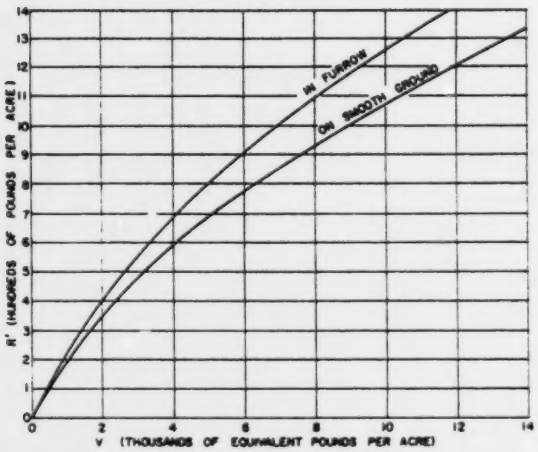



CHART TO DETERMINE V FROM R' OR R' FROM V OF LIVE OR DEAD SMALL GRAIN CROPS IN SEEDLING AND STOOLING STAGE, ABOVE SURFACE OF GROUND, FOR CROP IN 3-INCH-DEEP FURROW AS CREATED BY DEEP-FURROW DRILL ON SMOOTH GROUND.

FIGURE IV.3-7

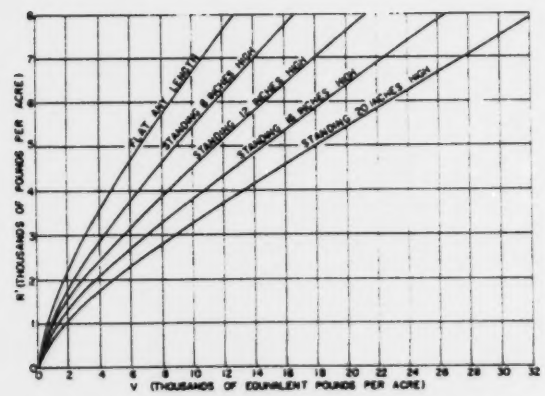

FLAT, ANY LENGTH
STANDING 8 INCHES HIGH
STANDING 12 INCHES HIGH
STANDING 16 INCHES HIGH
STANDING 20 INCHES HIGH
R' (THOUSANDS OF POUNDS PER ACRE)
V (THOUSANDS OF EQUIVALENT POUNDS PER ACRE)

CHART TO DETERMINE V FROM R' OR R' FROM V OF STANDING AND FLAT GRAIN SORGHUM STUBBLE OF AVERAGE STALK THICKNESS, LEAFINESS, AND QUANTITY OF TOPS ON GROUND.

FIGURE IV.3-8

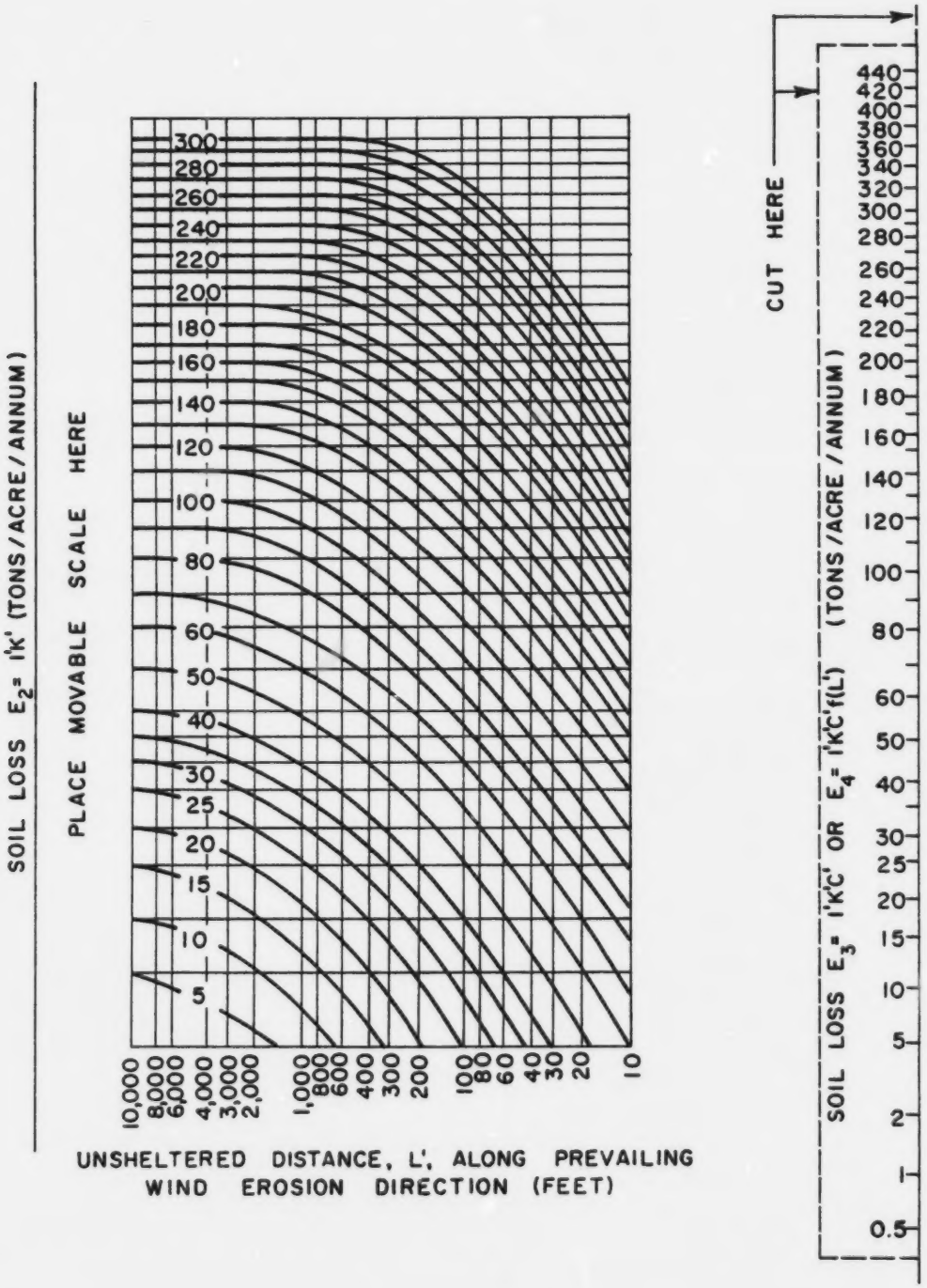



CHART TO DETERMINE SOIL LOSS $E_4$ = I'K'C'f(L') FROM SOIL LOSS $E_2$ = I'K' AND $E_3$ = I'K'C' AND FROM UNSHELTERED DISTANCE L' ACROSS FIELD.

FIGURE IV.3-9

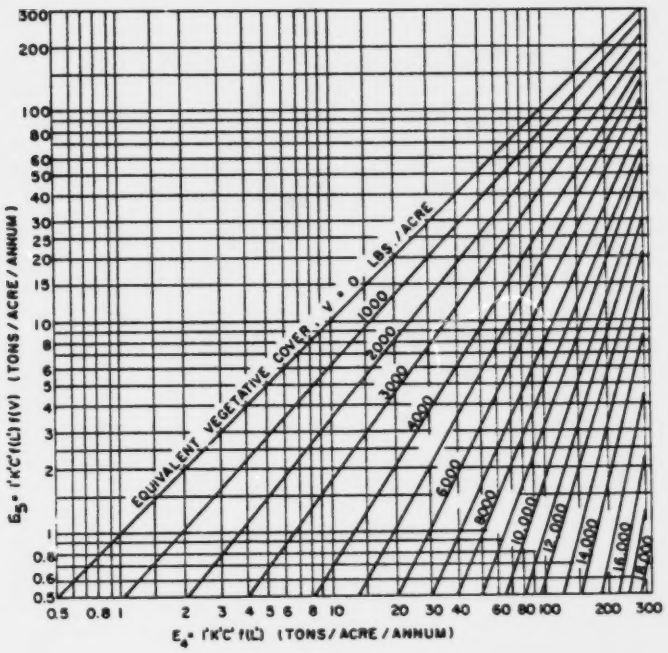



CHART TO DETERMINE SOIL LOSS E = I'K'C'f(L')f(V) FROM SOIL LOSS $E_4$ = I'K'C'f(L') AND FROM VEGETATIVE FACTOR V. CHART CAN BE USED IN REVERSE TO DETERMINE V NEEDED TO REDUCE SOIL LOSS TO ANY DEGREE.

FIGURE IV.3-10

cover possible; a forest cover would ensure maximum evapotranspiration, least percolation of precipitation into underlying wastes and maximum control of surface erosion.

Whether or not a regional type forest cover will evolve on the tailings or various covers which have or have not been revegetated with an herbaceous type vegetative cover, cannot, given the present knowledge of plant ecosystem development, be decisively answered. Reclamation studies in Canada are relatively new (mostly beginning in the late 1960's) and insufficient time has elapsed for definitive patterns in plant succession processes to be observed. The current belief that a forest type ecosystem will develop has been based a) on classical plant succession patterns for non-mining disturbed lands in each region and b) on sparse information (primarily visual observations) from tailings sites which have been revegetated during the past two decades. The possibility, that in fact the form of plant succession on revegetated disturbed mining lands will not follow traditional patterns has already been raised by several researchers (see III.2.7; IV.1.1). The authors suggest however, that caution is necessary in interpreting those trends when data has been collected over relatively short periods. Plant succession patterns on landslides in mountain foothills was investigated by Pandey and Singh (1985). Following the initial natural establishment of annual species, perennial forms established and were predominant after 13 years but continued to exhibit pattern changes up to 21 years. Shrubs were first noticed 6 years after the initial disturbance. Seedlings of certain pioneer tree species appeared early in the succession but climax tree species did not appear for almost 20 years. Forty years after the disturbances had occurred, juvenile trees of climax species were present but sparsely distributed. The time scale is indicative of the need not to prejudge or rigidly interpret patterns in evolving ecosystems on disturbed lands such as uranium tailings.

It is not within the scope of this report to provide a detailed discussion of forest succession systems or processes. It is the opinion of the authors that forest type communities will evolve over time on most non-acidic tailings, whether initially revegetated or not, and on the majority of capping materials used to ensure long-term stability. The floristic composition of those forest communities will likely be extremely variable. Diverse rooting environments will be created by various cover systems and that diversity will be reflected in the number and type of plant species able to exploit them.

It may be argued that the development of near identical regional forest communities on tailings and control covers is not an absolute requirement. The basic requirement of a vegetative community occurring on disturbed sites is that it is self-generating and self-perpetuating, provides maximum evapotranspiration, control of surface erosion and reduces surface infiltration. All plant communities, other than climax vegetation communities, exhibit successional processes; they are not static. Reclamation procedures implemented upon abandonment must therefore be designed to ensure that vegetation may persist and develop naturally. This entails that abandonment design must minimize the risk of catastrophic-type events such as flooding/ponding, severe erosion, acid generation and upward salt migration. Within the above context, the desired objective of a

regional type forest cover is not a prime requirement. Long term integrity of the vegetative cover should become the predominant consideration, not floristic composition.

Root development in itself can influence the structural stability of the cover system in which it is developing. The general pattern of root distribution is for the largest number of roots and the majority of fine roots to be located in the upper portion of the soil profile. Intensity of rooting in upper soil or cover layers often reflects soil fertility, temperature, aeration and the presence of soil moisture during the growing season. In many soils or covers, compact or permeable layers may restrict general root development. In soils where root penetration is restricted there are often places (eg. breaks in liners or low permeability barriers) where a root manages to grow through, and if more favourable environmental conditions exist under the layer, the root will proliferate in this region. Once the original root channel has been created succeeding generations of roots may make use of it (Armson and Williams, 1960).

Where root penetration is restricted by barriers or soil shallowness, those species in which the root form consists of laterals, some oblique roots and sinkers have an advantage over species with other root forms. This is true for eastern white pine in which the root system is capable of exploiting both lateral and vertical fissures in, for example, a fractured bedrock. Black spruce may be commonly found over a wide range of soils - thin soils over bedrock, organic soils with a fluctuating water table within 0.3m of the surface and on deep well-drained soils of various textures. Occupation of soil by roots is neither uniform nor static and this applies to communities of plants as well as to individual plants. As trees develop, both seasonally and over their lifespan, there is continual change in the root system.

Cover system design will have an important influence on the type and number of herbaceous, shrub and tree species that will be able to persist thereon. As previously described, cover thickness, presence of impermeable layers and drainage systems determine the seasonal availability of water in a cover system (Section III.5.1). In those cover systems where drainage controls do not occur, root activity is unlikely to impair the integrity of the system. Rather the environmental conditions of excessively high moisture may impair root system development. Where drainage controls are constructed, as an essential component of an engineered cover system, the lack of sufficient plant available water in the soil fraction of the system may well effect deep root development patterns. It is well known that roots "search out" water. Root growth into drains will substantially impair the efficiency of those drains over time.

Because of the diversity of waste disposal practices represented in past, current and future uranium mining operations, numerous cover design systems will occur. An assessment of vegetative community development (above and below ground) on each would require individual study, taking into account many climatic and edaphic factors within each. Future design of cover systems should include an assessment of such systems and their potential effect on long term stability of a vegetative cover, whether occurring naturally or being artificially established. Any systems should include the basic concept of providing a relatively well stabilized root growth

environment. That is to say, widespread seasonal fluctuation in environmental factors such as water table fluctuation, upward salt migration in summer months, excessive ponding of water during snow melt and storm periods, should be avoided by the cover system design.

The effects of biological penetration due to root growth can be summarized as follows:

(i) root penetration will occur through caps or covers which are not so dense or phytotoxic as to inhibit root penetration. This will result in the formation of permeable paths in the cap layers, reducing the low permeability characteristics of the cap.

(ii) root penetration into permeable drainage layers will result in the development of root decay products in these layers reducing the permeability of these zones.

Under conditions of healthy vegetative cover development it is anticipated that biological penetration will result in failure of these layers in considerably less than than the 1000 to 2000 year period of interest.

Biological penetration of the cover by burrowing animals will occur and small amounts of tailings will be brought to the surface. The release rate will be largely dependent on the depth of cover placed relative to the depth of the burrowing. The release rate is assessed to be small for tailings from the low grade Canadian ore deposits, but insufficient data exists to allow a quantitative estimate to be made.

### IV.3.4 GEOCHEMICAL EFFECTS AND PORE WATER CHANGES

#### IV.3.4.1 Estimated and Observed Tailings Pore Water Composition

Detailed estimations of pore water compositions for Canadian uranium tailings were made by Clifton Associates (1986). A summary of these values, combined with measured pore water compositions is given in Table IV.3-4 for Elliot Lake type, Key Lake type and Rabbit Lake type uranium tailings.

Overall, it is evident that the actual composition measured in the field is not radically different for most parameters from that which would be predicted by consideration of the ore/process chemistry. In addition, the actual composition - at least, initially - is effectively process dependent and is more representative of the milling process chemistry than of the original ore composition. The ore becomes important, however, as it is the source of the trace metals in the pore water and will influence the pore water composition for trace elements for extended periods in their geochemical evolution.

TABLE IV.3.4

TAILINGS PORE WATER COMPOSITIONS - ESTIMATED FROM ORE/PROCESS CHEMISTRY (A) AND MEASURED FOR 3 ORE TYPES (B) IN MG/L

| | Elliot Lake Tailings (a) | | Key Lake Type Tailings (est) | | Rabbit Lake Tailings | |
|---|---|---|---|---|---|---|
| | A | B | A | B | A | B |
| pH | 10 | 8-10 | 8-10 | 9.3-11.1 or 6.4-12 | 7-9 | 5.0-8.85 |
| TDS | 2000-3000 | 3000-5000 | 2000-4000 | - | 5000-8000 | 6000-8000 |
| Fe | 0.1-1.0 | <1 | 0.1-1.0 | 0.03-4 | 1 | 0.25 |
| $SO_4$ | 1500-2500 | 1000-2000 | 1500-2500 | 1350-1650 | 2000-5000 | 6400 |
| Ca | 600 | 400-500 | 600-800 | 580-630 | 600-1000 | 468 |
| Mg | <1-500 | N/A | <1 | 0.1-500 | <1-500 | 960 |
| Mn | N/A | N/A | N/A | <0.1-4 | N/A | 0.4 |
| Na | <50 | N/A | <50-500 | 20-200 | <50-1000 | 155 |
| K | N/A | N/A | N/A | 5-30 | N/A | 30 |
| Al | 0.2-6 | N/A | 0.2-6 | <0.1-6 | 0.1 | N/A |
| Cu | N/A | N/A | N/A | <0.01 | N/A | 0.06 |
| Co | N/A | N/A | N/A | <0.01 | N/A | 0.15 |
| Zn | N/A | N/A | N/A | 0.02-0.03 | N/A | 0.06 |
| Pb | N/A | N/A | N/A | <0.02-0.04 | N/A | 0.1 |
| Ni | <0.5 | N/A | <0.5 | 0.02-0.09 | <0.5 | 0.4 |
| $SiO_2$ | <5 | N/A | <5 | 1.8-4 | <5 | N/A |
| Cl | <50 | 50-100 | <50-500 | 10-400 | <50-1000 | 210 |
| $NH_3$-N | 100 | 50-100 | <10-100 | 10-30 | <10-500 | 350 |
| $NO_3$-N | <10 | N/A | <10 | <0.1 | <10 | 5 |
| As | <0.1-10 | N/A | 1-10 | 0.3-2.2 | <0.1 | 0.001 |
| Cr | N/A | N/A | N/A | <0.005 | N/A | 0.02 |
| Mo | N/A | N/A | N/A | 0.4-1.2 | N/A | N/A |
| U | N/A | N/A | N/A | 0.001-0.005 | N/A | 0.03-0.5 |
| W | N/A | N/A | N/A | 0.45-0.9 | N/A | N/A |
| $Th^{230}$ | N/A | 22-55 | <10-80 | 10-55 | 1-50 | 1-18 |

a - neutralized tailings, i.e., refers to "fresh", unweathered tailings.

est - combined estimate from various observations

A - estimated from ore/process chemistry

B - measured

N/A - not available

IV.3.4.2 Geochemical Evolution of Tailings Pore Water Composition

A very detailed appraisal and analysis of the change in geochemistry of pore water with time was made by Clifton Associates (1986), to which reference should be made. In essence, this demonstrated that the various pore water compositions given in Table IV.3-4 change with time, i.e., are subject to geochemical evolution. However, the changes in composition vary with both the type of ore and with time.

Essentially, four stages of geochemical evolution of pore water chemistry were recognized:

1. an initial process controlled stage;

2. a sulphide oxidation stage;

3. a resolution stage; and

4. a long term leaching stage.

For the resolution stage, two alternatives were identified, depending on the presence of pyritic sulphur in the original ore. Therefore, in the case of pyrite-bearing tailings, the pore water composition would evolve through stages 1, 2, 3 (alternative 1) and 4, while in the case of non-pyritic tailings, this stage would be 1, 3 (alternative 2) and 4. Typical compositions representing these changes for the three generic tailings types are shown in Table IV.3-5.

In terms of the rate of solute migration through the tailings, the effective recharge rate related to the inherent tailings permeability will control migration, where solution processes only operate, i.e., in stages 1, 3 and 4. In the case of the pyritic, acid generating tailings (Elliot Lake) type, other reactions need consideration. Dubrovsky et al (1985) predict a rate of migration downwards of the acidic bearing pore water in pyrite tailings of 0.2-2 m/yr. This rate of downward advance is slower than the infiltration rate/seepage rate, due to the retardation of the acid through neutralization, during solute transport.

The time for evolution of pore water composition in uranium tailings in Canada has not been well documented. Snodgrass et al (1982) erected a time scale for reactions in pyrite bearing tailings. They suggested:

TABLE IV.3-5

PORE WATER QUALITY CHANGES WITH TIME

| | Process Controlled Stage All Tailings | Sulphide Oxidation Stage Pyrite Bearing Tailings | Resolution Stage ** Pyrite Bearing Alternative 1 | Resolution Stage ** Non-Pyrite Alternative 2 | Long Term Infiltration Phase All Tailings |
|---|---|---|---|---|---|
| pH(units) | 10 | 2 | 3.5 | 7.5 | 5 |
| TDS | 4,500 | 30,000 | 2,500 | 2,500 | 100 |
| Ca | 600 | 500 | 400 | 400 | 20 |
| $SO_4$ | 3,000 | 20,000 | 1,800 | 1,200 | 10 |
| $NH_3$ | 300 | <10 | <10 | 100 | <1 |
| Na | 100 | 100 | 20 | 50 | 10 |
| Cl | 200 | 200 | 20 | 20 | 10 |
| Fe | <1 | 10,000.* | 20 | 5 | <1 |
| Mg | 100 | 200 | 50 | <5 | 10 |
| $As_{226}$ | 1 | 1 | <1 | <1 | <0.1 |
| $Ra_{226}$ | <20 | <5 | <20 | <10 | <10 |
| Al | <5 | 20 | 20 | <5 | 5 |
| Si | <5 | 20 | 20 | <5 | 5 |

* If oxidizing ore is pyrite or iron-bearing sulphide

** May be accompanied by alteration of jarosite, in iron-bearing tailings

0-165 years
- sulphate production from pyrite oxidation in acid solution;
- calcium availability from acid neutralization by carbonates;
- calcium sulphate from gypsum solution;
- formation of jarosite and then goethite, which can limit iron in solution;

160-185 years
- increased calcium sulphate solution under acidic conditions;
- goethite solution increases iron concentrations;
- final oxidation of all pyrite;

185-400 years
- increasing pH to about 5/6;
- continued gypsum solution.

This effectively only covers the first three stages of pore water evolution for pyrite bearing tailings. Application of a similar timescale for the four evolutionary stages of pore water composition for the three generic tailings types would give:

0-20 years (or impoundment operational life) - process controlled stage

20-200 years - sulphide oxidation stage

150-600 years - resolution stage

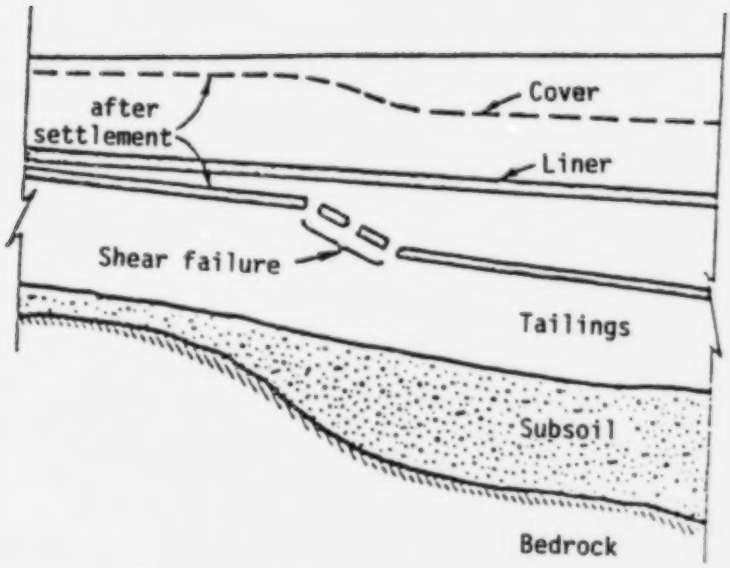
500-1000+ years - long term leaching stage

## IV.3.5 PHYSICAL INSTABILITY

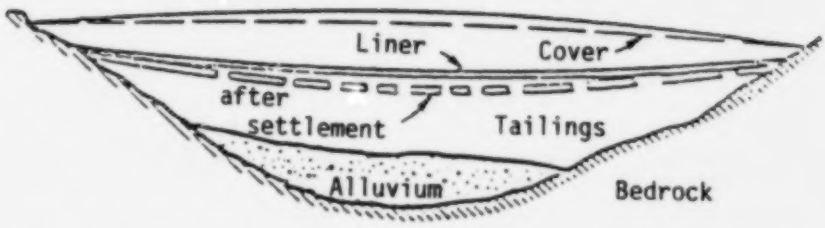
### IV.3.5.1 Differential Settlement

Where a covering layer serves as a barrier to inhibit either radon emanation or surface infiltration it may fail as a result of differential settlement. Both shear and tension failures can occur as illustrated in Figure IV.3-11. Because of the greater moisture content in surface soil layers in the uranium producing areas of Canada, the need for radon barriers is less than for equivalent uranium tailings deposits in the U.S.A. Isolated cracking would not result in a significant increase in radon emanation. However, where the barrier serves to inhibit seepage, it is expected that mounding (ponding) of water may develop on the barrier layer. With mounding there is a hydraulic gradient which would induce flow towards any cracks in the barrier which allow flow into the underlying tailings.

This failure mechanism may be particularly significant with regard to tailings from the high grade ores being processed in Saskatchewan.




(a) Shear Displacement




(b) Tension Failure

FAILURE OF COVER DUE TO DIFFERENTIAL SETTLEMENT
(NELSON AND SHEPHERD, 1978)

FIGURE IV.3-11

Causes of differential settlement are:

- an uneven bedrock topography,
- compressible foundation strata
- different consolidation characteristics in different tailings zones
- differential dewatering
- frost action
- differential loading

Differences in consolidation characteristics result from the segregated nature of many tailings deposits. The coarse and fine zones have different compressibility characteristics and consolidate at different rates. Large differential settlements can occur where tailings are frozen at a low density on placement and later thaw and consolidate. The consolidation theory for uranium tailings impoundments is defined in Nelson et al, 1983, and Fayer and McKeon, 1984, which also include a description of measures which may be considered to accelerate compaction.

Techniques which accelerate compaction include pre-loading, blast induced consolidation, dynamic compaction, vibratory compactors, the method of tailings deposition, and tailings dewatering. Most of these methods have limited success and application.

Cracking can be reduced by constructing the cover barriers using flexible, ductile materials. Soft clays are less rigid than silt or clayey sand layers and would suffer less cracking when subjected to differential settlements. There is a paucity of clay in the Canadian uranium producing areas, and tills are usually the least permeable materials which are available and suitable for constructing low permeability caps. These are expected to be relatively brittle and susceptible to cracking.

Where the clay cap is constructed overlying a coarse permeable suction break layer, the rate of infiltration through cracks in the cap could be large (and may result in piping failure) and render the cap ineffective as an infiltration inhibitor.

It is concluded that there is a very high likelihood that this form of instability will effect parts of most covers, which include a radon or infiltration inhibiting cap layer, within a relatively short time after reclamation. The increased release rate for radon is considered to be insignificant. Increases in infiltration could be large, particularly where an underlying suction break coarse layer is also installed. Infiltration rates are evaluated in Section IV.3.6.

IV.3.5.2 Shrinkage

Fine grained soils masses are often dimensionally unstable when subjected to variations in moisture content. When drying out, high pore water

suction pressures are generated in such fine grained soils resulting in consolidation and cracking.

It may be anticipated that surface caps placed over tailings impoundments will be subjected to large variations in moisture conditions. This moisture variation will depend on:

- initial moisture content at placement
- depth of any covering layer
- any overlying drainage layer
- nature of vegetative cover (root suction)
- climatic cycles (precipitation and evaporation)

Moisture variations between saturation and that at the wilt level for the vegetative cover (or less) can be anticipated. This would be sufficient to cause cracking in most fine grained low permeability capping layers.

The extent of cracking will depend on the linear shrinkage coefficient of the capping material (Mitchell, 1976). Active clays have high linear shrinkage values while silts from glacially produced rock flour have a low linear shrinkage. Granular materials such as sands are dimensionally stable and do not shrink with drying out. The linear shrinkage, for any moisture change can be readily determined in the laboratory. Where a small proportion of clay (such as bentonite) is mixed with sand, the sand grains provide a rigid, dimensionally stable skeleton and low linear shrinkage rates can be achieved.

Since the cap material consolidates during the shrinkage process, the cracks do not necessarily close when the layer is again wetted. Also, roots and or material from the overlying layers penetrate or are washed into the cracks rendering them permanently higher permeability pathways.

Where caps are constructed of a clay rich soil, extensive cracking is anticipated in the long term rendering the cap ineffective as a low permeability layer. Tills are generally the most suitable material for cap construction at Canadian uranium tailings sites. These materials generally have fairly low linear shrinkage values. The potential for shrinkage would have to be investigated for the particular materials under consideration. It is anticipated that some cracking will occur. The stability of sand and bentonite cap mixtures will depend on the proportion of bentonite used.

Changes in the chemical composition of the cap material can also result in dimension changes and shrinkage (Mitchell 1976). Where caps are formed from local natural materials, this is not considered to be a significant cause of cover instability.

Release rates for cracks due to shrinkage are similar to those for differential settlement discussed in the previous section.

IV.3.5.3 Frost Action

The tailings pile and the cover will be subjected to annual freeze thaw cycles. The frost action can affect the cover-tailings system by:

a) permafrost aggradation
b) frost "pumping" of pore fluid
c) degrading cap or liner permeability

IV.3.5.3.1 Thermal Analysis

A thermal analysis of the tailings-cover system was carried out to determine the anticipated depth of freezing and thawing for the range of climatic, surface, cover and tailings conditions anticipated.

A simplified, two layer thermal model was used (Andserland and Anderson, 1978). The model predicts the depth of thaw or frost penetration considering the volumetric latent heat, the thermal conductivity of the freezing-thawing zone and the equivalent soil surface temperature. A linear temperature profile is assumed. The model neglects the specific heat above and below the frost front, the unfrozen moisture content of the soil and the geothermal gradient. These assumptions tend to overpredict the depth of frost penetration. The model considers heat exchange at the ground surface by empirically relating the soil surface temperature to the air temperature in terms of freezing/thawing indices.

The range of environmental and soil parameters used in the analysis is presented in Table IV.3-6. Parameters selected are representative of Saskatchewan uranium mining areas. The range of predicted freezing and thawing depths are presented in Figure IV.3-12.

For equal frost and thaw depths there is an incipient tendency for permafrost formation. In Figure IV.3-12 the area above the diagonal line illustrates conditions favourable for permafrost formation while areas below the line illustrate conditions unfavourable for permafrost formation.

The Saskatchewan sites are located in the zone of discontinuous permafrost. Permafrost is not naturally occurring in the Elliot Lake area, however, the thermal analysis of the high moisture content tailings showed a tendency toward permafrost aggradation. In most of the cases analyzed, the seasonal depth of frost was greater than the seasonal depth of thaw, which would result in development of perennially frozen soil. Permafrost has not been observed in the Elliot Lake tailings (Denison Mines, Personal Communication) but has been observed in the Saskatchewan tailings impoundments.

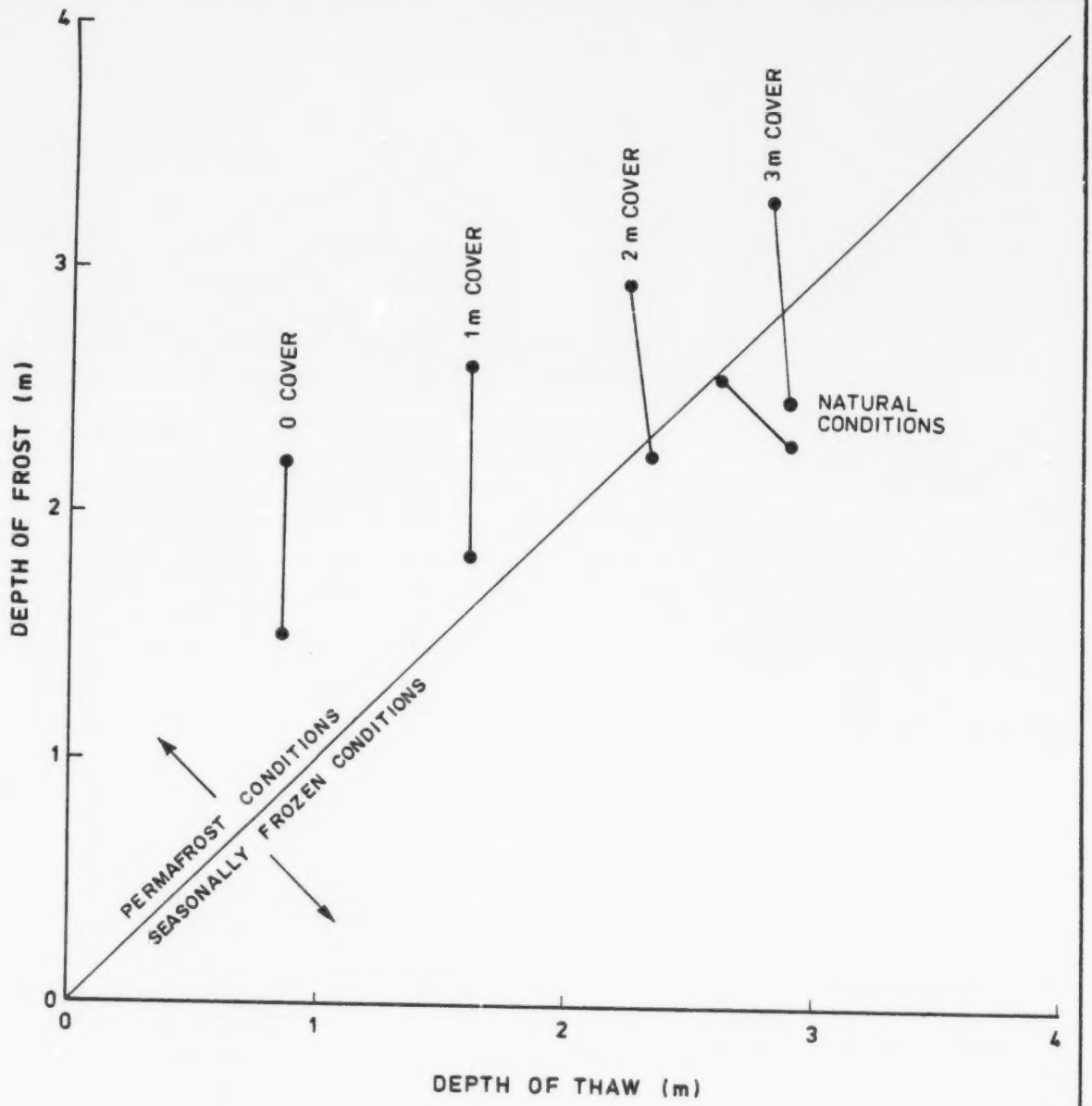
Permafrost is favoured in the tailings and not in the natural soil because the tailings possess a much higher moisture content. The ratio between the frozen and thawed thermal conductivity is much higher for the wet tailings than it is for the drier natural soil. Therefore, in wet tailings the freezing process is favoured over the thawing process. For typical tailings with a moisture content of 90%, the ratio between frozen and thawed thermal conductivity is about 3.7 while for the natural soil it is about 1.4.

TABLE IV.3-6

THERMAL MODEL PARAMETERS
(Typical of Saskatchewan Uranium Mining Areas)

| PARAMETER | UNITS | RANGE | NATURAL SOIL |
|---|---|---|---|
| Freezing index | deg C days | 2780 - 3260 | |
| Thawing index | deg C days | 1740 - 1540 | |
| "n" factor freezing | | .5* - .9** | .29*** |
| "n" factor thawing | | 1.0* - 1.8** | .37*** |
| Tailings | | | |
| moisture content | % | 120 - 90 | |
| dry density | Mg/cu. m. | .6 - .75 | |
| frozen thermal cond. | W/m C | 2.2 | |
| thawed thermal cond. | W/m C | 0.6 | |
| volumetric latent heat | MJ/cu. m. | 240 - 225 | |
| Cover | | | |
| moisture content | % | 8 - 15 | 15 |
| dry density | Mg/cu. m. | 2 - 1.8 | 1.9 |
| frozen thermal cond. | W/m C | 3.4 - 3.7 | 3.7 |
| thawed thermal cond. | W/m C | 2.4 - 2.7 | 2.7 |
| volumetric latent heat | MJ/cu. m. | 50 - 90 | 95 |

Notes:
* vegetated surface
** bare surface
*** forested




COMPARISON OF FREEZING AND THAWING DEPTHS FOR TYPICAL SASKATCHEWAN CONDITIONS

FIGURE IV.3-12

Referring to Figure IV.3-12, for no cover with the high water content tailings near the surface, the thaw penetration is only about 0.5 of the frost penetration while for thicker low moisture content covers, the frost conditions more closely approximate that of the surrounding terrain and the thaw depth is closer to or greater than the frost depth.

Another factor which favours permafrost aggradation is semi-dry or layered tailings deposition where the tailings surface is exposed during deposition. It freezes and is prevented from thawing by additional summer deposited tailings.

The implications with respect to mass transfer is that the pore fluid cannot be released from frozen tailings. Frost would also be an effective barrier against radon release. In the long-term, climatic changes could reverse the present balance and initiate a much delayed release of the tailings pore fluid. Such releases would be accompanied with consolidation and settlement of the cap and cover.

As for the case of seasonal thaw, discussed in detail in the following section, the rate of fluid generation upon thaw would be only marginally greater than the potential evapotranspiration, therefore little free fluid would be released to the surface water.

IV.3.5.3.2 Mass Transfer by Frost Action and Frost Heave

Permafrost aggradation appears to be favoured in the tailings. However, there is some uncertainty in the simplified model used. This section discusses the potential for frost action to transport tailings pore fluid to the surface, assuming that permafrost conditions do not develop.

Frost action on the tailings surface can result in "pumping" of water in the tailings pile at depth to the surface. The mechanisms are:

a) Ice segregation and flow of water to the freezing front during freezing;

b) Subsequent thawing and release of water to the surface;

c) Evaporation of water released to surface.

A frost heave model was developed using the heave theory of Konrad and Morgenstern (1982a). The model predicts the amount of ice segregational heave as a function of the soil temperature gradient, the fluid suction pressures at the freezing front and the overburden pressure at the freezing front. Greater ice segregation occurs with greater temperature gradient, lower fluid suction and lower overburden pressure.

The tendency for the soil to develop segregated ice is characterized by the segregation potential, SP which is the ratio of the velocity of water uptake divided by the temperature gradient at the freezing front.

The SP varies according to the overburden pressure Pe by the following relationship

$$SP = SPo \times e^{(-B\ Pe)}$$

A similar relationship, within limits, exists for the suction pressure; Pu;

$$SP = SPo \times e^{(-APu)}$$

Konrad and Morgenstern, (1981, 1982a, 1982b) present extensive laboratory testing of heave parameters for Devon silt. This material has a similar gradation to uranium tailings and the properties were used directly in the analysis. The parameters are as follows.

| | | | |
|---|---|---|---|
| Segregation potential | SP | $1.2 \times 10^{-9}$ | $m^2/°C\text{-sec}$ |
| Suction parameter | A | .0397 | 1/kPa |
| Overburden parameter | B | .00895 | 1/kPa |

Table IV.3-7 is an example model output showing the soil parameters used, the predicted frost depth and ice segregation with time.

Several cases were analyzed and the amount of ice segregation for various depths to water determined. The first case was no cover and a bare surface which provided the most ice segregation. No cover, vegetated, and vegetated cover of 0.6 and 3 meters in thickness were evaluated.

The results are presented in Figure IV.3-13. For the worst case of zero cover, bare site and a depth to the water table of 1 m, the predicted amount of water freezing as segregated ice is 180 mm. When the surface is vegetated, the ground surface temperature is moderated and the amount of heave reduces. Cover reduces the heave by virtue of the applied surcharge and the insulating properties of the layer. At 3 metres of cover there is virtually no heave. The amount of heave decreases rapidly with increasing depth to the water table.

In summary, depending upon the surface, water and cover conditions, a considerable amount of water can be transported from the unfrozen tailings mass and incorporated as ice in the seasonally frozen zone.

The second aspect of release by frost action is thawing. The thaw progresses from the top down. Any excess ice which thaws is liberated to the ground surface. It cannot flow downward because of the underlying frost. The rate at which water is released is described by the thaw consolidation theory (Morgenstern & Nixon, 1971). The rate at which water is liberated is determined by the rate of thaw. The rate at which it can dissipate to the surface is controlled by the soil permeability and compressibility. For the typical thaw rates and tailings properties evaluated, the average degree of consolidation of the tailings during thaw is 95%, i.e., the pore water pressures dissipate almost entirely to their hydrostatic state. This implies that the thawing water is almost immediately released to surface.

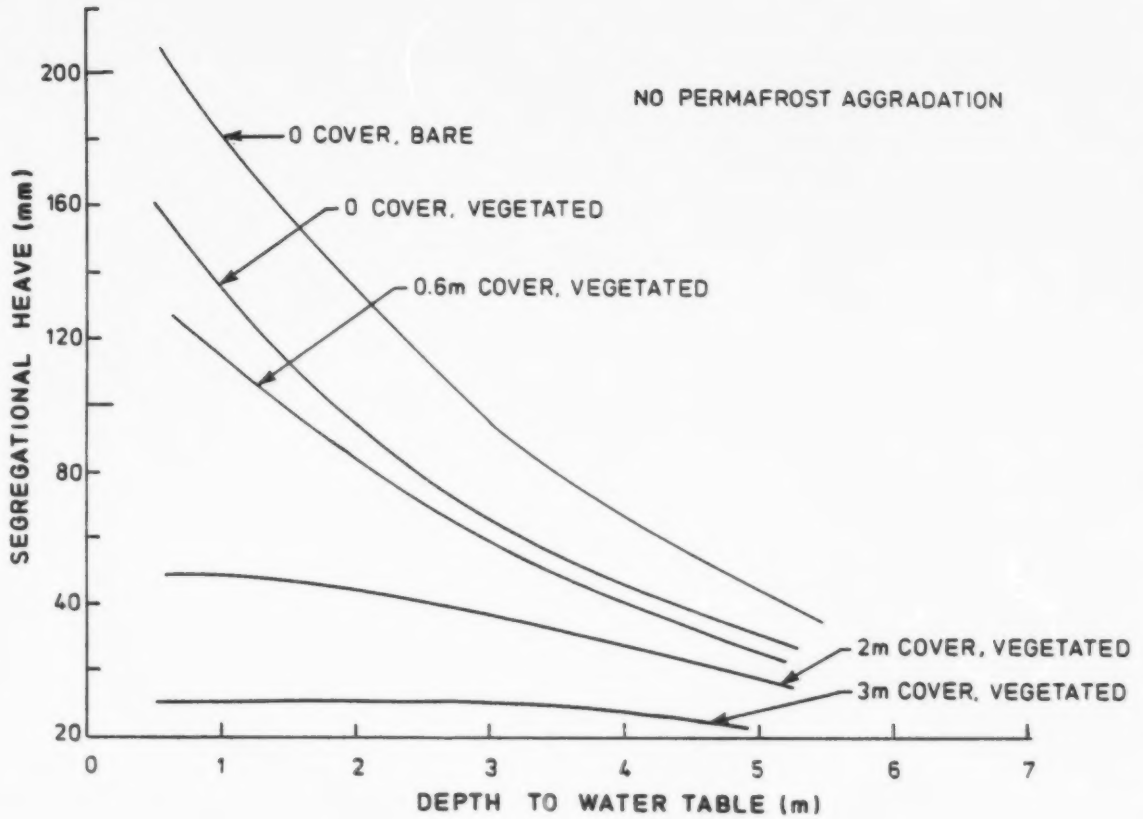
As the water is released it can flow to drainage or be evaporated. Water in excess of the amount evaporated will flow. The potential

TABLE IV.3-7

TAILINGS FROST HEAVE MODEL
W.T. TAILINGS

| SOIL PROPERTIES | (units) | TAILINGS | COVER |
|---|---|---|---|
| Cover thickness | m | n/a | 1 |
| Moisture content | % | 90 | 8 |
| Dry density | $Mg/m^3$ | 0.75 | 2 |
| Total density | $Mg/m^3$ | 1.425 | 2.16 |
| Frozen conductivity | W/mC | 2.2 | 3.5 |
| Thawed conductivity | W/mC | 0.6 | 2.7 |
| Frozen specific heat | $J/m^3C$ | 1.94E+06 | 1.76E+06 |
| Thawed specific heat | $J/m^3C$ | 1.06E+06 | 1.72E+06 |
| Volumetric latent heat | $J/m^3$ | 2.25E+08 | 5.34E+07 |
| Normalized SP | $m^2/C$ sec | 1.20E-09 | 1.20E-09 |
| SP suction parameter | $kPa^{-1}$ | 3.97E-02 | 3.97E-02 |
| SP overburden parameter | $kPa^{-1}$ | 8.95E-03 | 8.95E-03 |
| ENVIRONMENTAL PARAMETERS | | | |
| Freezing Index | C-days | 2775 | |
| Thawing Index | C-days | 1740 | |
| Length of frost season | days | 185 | |
| n freezing | | 0.5 | VEGETATED |
| n thawing | | 1 | VEGETATED |
| Equiv. freeze step temp | C | 7.5 | |
| Equiv thaw step temp | C | 9.67 | |
| Depth to water | m | 5 | |
| Time step | days | 5 | |

| TIME | TIME | FROST DEPTH | TEMP. GRAD. | SUCTION | OVER BURDEN | SEG. POT. | WATER FLUX | CUM. WATER | THAW DEPTH |
|---|---|---|---|---|---|---|---|---|---|
| days | sec. | m | °C/m | kPa | kPa | $m^2/C$ sec | m/sec | mm | m |
| 5 | 4.32E+05 | 0.65 | 0.00 | 42.62 | 13.79 | 2.0E-10 | 0 | 0.00 | 0.65 |
| 10 | 8.64E+05 | 0.92 | 0.00 | 39.97 | 19.50 | 2.1E-10 | 0 | 0.00 | 0.92 |
| 15 | 1.30E+06 | 0.96 | 0.00 | 39.58 | 20.35 | 2.1E-10 | 0 | 0.00 | 1.13 |
| 20 | 1.73E+06 | 1.01 | 11.70 | 39.08 | 21.34 | 2.1E-10 | 2.46E-09 | 1.06 | 1.07 |
| 25 | 2.16E+06 | 1.06 | 10.89 | 38.61 | 22.01 | 2.1E-10 | 2.32E-09 | 2.06 | 1.11 |
| 30 | 2.59E+06 | 1.10 | 10.23 | 38.18 | 22.63 | 2.2E-10 | 2.20E-09 | 3.01 | 1.14 |
| 35 | 3.02E+06 | 1.15 | 9.68 | 37.76 | 23.21 | 2.2E-10 | 2.11E-09 | 3.92 | 1.17 |
| 40 | 3.46E+06 | 1.19 | 9.20 | 37.37 | 23.77 | 2.2E-10 | 2.02E-09 | 4.80 | 1.20 |
| 45 | 3.89E+06 | 1.22 | 8.80 | 37.00 | 24.30 | 2.2E-10 | 1.95E-09 | 5.64 | 1.22 |
| 50 | 4.32E+06 | 1.26 | 8.44 | 36.65 | 24.81 | 2.2E-10 | 1.89E-09 | 6.46 | 1.25 |
| 55 | 4.75E+06 | 1.30 | 8.12 | 36.31 | 25.29 | 2.3E-10 | 1.84E-09 | 7.26 | 1.27 |
| 60 | 5.18E+06 | 1.33 | 7.83 | 35.98 | 25.76 | 2.3E-10 | 1.79E-09 | 8.03 | 1.29 |
| 65 | 5.62E+06 | 1.36 | 7.58 | 35.66 | 26.22 | 2.3E-10 | 1.75E-09 | 8.78 | 1.31 |
| 70 | 6.05E+06 | 1.39 | 7.34 | 35.35 | 26.65 | 2.3E-10 | 1.71E-09 | 9.52 | 1.33 |
| 75 | 6.48E+06 | 1.42 | 7.13 | 35.05 | 27.08 | 0.000000 | 1.67E-09 | 10.24 | 1.35 |
| 80 | 6.91E+06 | 1.45 | 6.93 | 34.76 | 27.49 | 0.000000 | 1.64E-09 | 10.95 | 1.37 |
| 85 | 7.34E+06 | 1.48 | 6.75 | 34.48 | 27.90 | 0.000000 | 1.61E-09 | 11.64 | 1.39 |
| 90 | 7.78E+06 | 1.51 | 6.59 | 34.20 | 28.29 | 0.000000 | 1.58E-09 | 12.32 | 1.41 |
| 95 | 8.21E+06 | 1.54 | 6.43 | 33.93 | 28.67 | 0.000000 | 1.55E-09 | 12.99 | 1.43 |
| 100 | 8.64E+06 | 1.56 | 6.29 | 33.67 | 29.05 | 0.000000 | 1.53E-09 | 13.65 | 1.44 |
| 105 | 9.07E+06 | 1.59 | 6.15 | 33.41 | 29.41 | 0.000000 | 1.51E-09 | 14.30 | 1.46 |
| 110 | 9.50E+06 | 1.62 | 6.03 | 33.16 | 29.77 | 0.000000 | 1.48E-09 | 14.95 | 1.47 |
| 115 | 9.94E+06 | 1.64 | 5.91 | 32.92 | 30.12 | 0.000000 | 1.47E-09 | 15.58 | 1.49 |
| 120 | 1.04E+07 | 1.67 | 5.79 | 32.67 | 30.47 | 0.000000 | 1.45E-09 | 16.20 | 1.51 |
| 125 | 1.08E+07 | 1.69 | 5.69 | 32.44 | 30.81 | 0.000000 | 1.43E-09 | 16.82 | 1.52 |
| 130 | 1.12E+07 | 1.71 | 5.59 | 32.20 | 31.14 | 0.000000 | 1.41E-09 | 17.43 | 1.54 |
| 135 | 1.17E+07 | 1.74 | 5.49 | 31.98 | 31.46 | 0.000000 | 1.40E-09 | 18.04 | 1.55 |
| 140 | 1.21E+07 | 1.76 | 5.40 | 31.75 | 31.78 | 0.000000 | 1.38E-09 | 18.63 | 1.56 |
| 145 | 1.25E+07 | 1.78 | 5.31 | 31.53 | 32.10 | 0.000000 | 1.37E-09 | 19.22 | 1.58 |
| 150 | 1.30E+07 | 1.80 | 5.23 | 31.31 | 32.41 | 0.000000 | 1.36E-09 | 19.81 | 1.59 |
| 155 | 1.34E+07 | 1.83 | 5.15 | 31.10 | 32.72 | 0.000000 | 1.34E-09 | 20.39 | 1.61 |
| 160 | 1.38E+07 | 1.85 | 5.08 | 30.89 | 33.02 | 0.000000 | 1.33E-09 | 20.96 | 1.62 |
| 165 | 1.43E+07 | 1.87 | 5.01 | 30.68 | 33.31 | 0.000000 | 1.32E-09 | 21.53 | 1.63 |
| 170 | 1.47E+07 | 1.89 | 4.94 | 30.47 | 33.61 | 0.000000 | 1.31E-09 | 22.10 | 1.65 |
| 175 | 1.51E+07 | 1.91 | 4.87 | 30.27 | 33.89 | 0.000000 | 1.30E-09 | 22.66 | 1.66 |
| 180 | 1.56E+07 | 1.93 | 4.81 | 30.07 | 34.18 | 0.000000 | 1.29E-09 | 23.22 | 1.67 |
| 185 | 1.60E+07 | 1.95 | 4.75 | 29.87 | 34.46 | 0.000000 | 1.28E-09 | 23.77 | 1.68 |




POTENTIAL TAILINGS FROST HEAVE, W.T. SITE
NORTHERN SASKATCHEWAN

FIGURE IV.3-13

evapotranspiration for the site was estimated from climatological data by the Thornthwaite method.

The potential evapotranspiration, the net potential evaporation above rainfall, and the potential for water release during the summer months are shown in Table IV.3-8.

In May, June, September and October, the rainfall plus the fluid released from thawing is greater than the potential evapotranspiration for the zero or "0" cover case. In the summer months, the evapotranspiration is much larger. On this basis, there is a potential annual release of 57 mm of fluid in Case 1 (0 cover, bare surface, water at 1 m) and 15 mm in Case 2 (0 cover, bare surface, water at 3 m). For other cases, the heave is reduced and the evaporation capacity is in excess of the thaw release. Any flow which does occur will be in the spring and may be confused with surface runoff from snowmelt and/or rainfall.

Pumping action will also tend to concentrate the dissolved constituents near the tailings surface by succeeding cycles of transport and evaporation.

The pumping action would continue until the tailings were sufficiently dewatered to reduce the amount of seasonal heave. Since the amount of heave is strongly influenced by the depth to the water table, and the water table is depressed by either frost pumping or evaporation to approximately the 3 metre mark, there would be little continued fluid transport. Assuming an initial moisture content of 90% and an unsaturated moisture content of 30%, approximately 800 mm of water could be removed to depress the water table 3 m. By frost pumping alone, at a rate of 60 mm/year this process would take approximately 13 years. The effects of evaporation and infiltration should also be addressed. Infiltration into the tailings will replenish the extracted fluid and prolong the frost "pumping" mechanism. For 60 mm of annual infiltration (16% of precipitation) the fluid pumped by frost would be annually replaced and the frost "pumping" could continue indefinitely.

IV.3.5.3.3 Summary

The thermal analysis suggests that permafrost conditions will develop in the tailings. Assumptions and simplifications in the simple thermal model used tend to overpredict the depth of frost; however, there appears to be a strong tendency for permafrost aggradation, especially under thin cover conditions.

Should permafrost conditions develop, then there is a very small potential for release of the tailings pore water. If, on the other hand, the model proves incorrect, there is a potential for pore water release of up to 60 mm/year by "frost pumping". A significant volume of water can be transported to the surface, however, only during the early summer and late fall will the rate of fluid release exceed the potential rate of evaporation. For the bare tailings surface, the maximum release was 60 mm. The amount of release decreased rapidly with increasing cover thickness and depth to the water table.

TABLE IV.3-8

POTENTIAL RELEASE AND EVAPOTRANSPIRATION

| Month | Potential Evapotrans-piration (mm) | Mean Precipitation (mm) | Evapotrans-piration less Precipitation (mm) | Water Released Case 1 (mm) | Case 2 (mm) |
|---|---|---|---|---|---|
| May | 56.7 | 23.5 | 33.2 | 59 | 27 |
| June | 109.3 | 42.4 | 66.9 | 35 | 17 |
| July | 124.5 | 67.3 | 57.2 | 27 | 14 |
| August | 104.2 | 52.1 | 52.1 | 22 | 13 |
| September | 52.6 | 44.9 | 7.7 | 19 | 11 |
| October | 11.9 | 30.3 | -18.4 | 19 | 11 |

Case 1 - no cover, bare surface, water at 1 metre.
Case 2 - no cover, bare surface, water at 3 metre.

"Frost pumping" would continue until sufficient fluid has been removed to drop the water table to a depth where frost heave no longer occurs. Roughly 800 mm of fluid over a 12 year period would have to be removed to lower the water table to 3 m depth. This rate ignores both infiltration and evaporation.

IV.3.5.3.4 Appropriate Technology

The technology considered to limit pore fluid release consists of methods to promote freezing, methods to limit frost heaving or intercept any produced fluid.

Freezing of the tailings will prevent hydraulic release of tailings pore fluid as well as retard radon release. The heave balance favours formation of permanent frozen tailings. If this method were pursued, design elements would consist of a thin, non-insulating cover. Vegetation would reduce but not preclude permafrost aggradation. If forest vegetation were to develop, the tendency to permafrost would be reduced further.

One way to promote freezing is by refrigeration of the tailings using thermal-pile techniques. These devices, one of which is the Cryo-anchor manufactured in Edmonton, remove heat from the ground during the winter. These are passive devices which require no external energy. They are essentially a hollow tube filled with a condensing fluid. An evaporator section is buried and a condensor with radiator exposed to the atmosphere. During the winter, the fluid evaporates in the soil, extracting heat. The vapour rises to the radiator section where it condenses and flows back to the evaporator section. These devices could be installed in bore holes from the tailings surface. They would extract heat in addition to the natural heat extracted during winter and promote and maintain permafrost conditions. They are very rugged and robust but they would be subject to mechanical breakage, corrosion and vandalism.

Cryo-anchors were extensively used on the Alaska pipeline to stabilize permafrost and prevent pipeline heave and settlement.

Further thermal analysis would be required to evaluate their effectiveness and cost. They may have short-term application in initiating permafrost conditions which would be maintained by natural conditions.

It is difficult to predict future climatic changes. There is even some controversy whether the world climate is warming or cooling. A small warming of the climate in the 2000 year time frame could result in degradation of permanently frozen tailings and subsequent release of the pore fluid. In such a case, the rate of release would likely be small because of the potential evapotranspiration.

Cover design should consider the potential for release of "pumped" pore water. If a zoned cover is used with a lower granular section, frost action could pump water into this strata. Collection systems would then be required to safely handle or contain this fluid.

Cover design should also consider the effects of frost on the impermeable section of the cover. Reduction in permeability and frost susceptibility should be considerations in design.

IV.3.6 INFILTRATION

An important factor in the decommissioned tailings pile water balance is the amount of water infiltrating the ground surface and reporting to the groundwater system (groundwater recharge). The physics of infiltration for a single rainfall event are summarized in Section III.6. The amount depends upon the soil and rainfall intensity-duration characteristics. The infiltration theory has been developed primarily as a component of runoff estimation. Water which infiltrates does not all report immediately to the groundwater system but a portion is subsequently consumed by evapotranspiration. Therefore, infiltration theory is not explicitly appropriate in estimating groundwater recharge; however, similar factors affect both processes.

The following infiltration estimates for various cover systems presented following are based on fairly broad assumptions. On a Saskatchewan wide basis (biased to the south) the maximum groundwater recharge is estimated at approximately 10% of mean annual precipitation. The higher groundwater table conditions, generally more pervious soils and lower evapotranspiration in the Northern uranium producing areas would tend to increase this ratio. Therefore, a conservative estimate of recharge of 20% of mean annual precipitation for a vegetated surface was selected. This compares with a range of infiltration used in water balance studies from less than 10% at Key Lake to 50% at Cluff Lake.

Some factors affecting infiltration are:

- surface cover
- soil characteristics
- slope

The surface cover affects infiltration and recharge. Table IV.3-9 shows relative infiltration rates for various soil textures and cover conditions. Bare soil has the least infiltration with denser vegetative cover providing more infiltration. Finer textured soils possess a lower infiltration rate. The difference in infiltration between coarse and fine textured soils varies by about 1 order of magnitude, a much lower variation than would be expected on the basis of soil permeability alone. The difference is attributed to secondary soil structure and the promotion of infiltration by soil suction. Suction is greater in the fine grained, low permeability soil and reduction in flow by low permeability is in part offset by higher initial suction.

The infiltration rate increases with the degree of vegetation because of the tilth and water retention capability provided by the vegetation. This cannot be directly transposed, however, to groundwater recharge because the denser vegetation also results in increased evapotranspiration. Field studies undertaken in northern Saskatchewan by Saskatchewan Highways and Transportation showed that where borrow pits were cleared the year before construction, the soil had a greater moisture content, sometimes up to 5%

TABLE IV.3-9

NET INFILTRATION RATES FOR UNFROZEN SOILS
(INCHES PER HOUR)
(GRAY, 1970)

| SOIL PROFILE CATEGORY | GROUND COVER CONDITIONS | | | | | |
|---|---|---|---|---|---|---|
| | BARE SOIL | ROW CROPS | POOR PASTURE | SMALL GRAINS | GOOD PASTURE | FORESTED |
| I | 0.3 | 0.5 | 0.6 | 0.7 | 1 | 3 |
| II | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| III | 0.05 | 0.07 | 0.1 | 0.15 | 0.2 | 0.25 |
| IV | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |

Category I: Coarse and medium textured soils over sand and gravel, glacial outwash materials or, coarse open till or, coarse alluvial deposits

Category II: Medium textured soils over medium textured till

Category III: Medium and fine textured soils over fine textured clay till

Category IV: Soil over shallow bedrock (two feet or less).

greater, than borrow pits cleared immediately before construction. Clearly, the dense vegetation resulted in a net drying of the soil and reduced recharge.

Slope is also a factor in infiltration rates. For flat slopes up to 5%, the slope will have little impact on recharge because local undulations will be present and minor ponding, which promotes infiltration, will be present. As the slope increases to about 6 horizontal to 1 vertical a significant reduction in infiltration occurs.

The cover design will significantly affect infiltration, particularly the stratification in thick cover. Alternative cover designs are presented in TMII. For a decreasing permeability cover (rock, soil, soil-bentonite) the water will pond in the rock and infiltrate the soil and soil-bentonite layers. The rock will act as a sink, promoting infiltration while retarding runoff and evapotranspiration. Such a sequence would have the highest infiltration. For flat slopes, water could accumulate in the rock and soil layers and drown the vegetation (E. Watkins, personal communication).

The alternative cover is an intermediate drain (soil, rock,soil-bentonite). The rock, which is designed to operate as a suction barrier to prevent desiccation of the soil-bentonite, also acts as a drain during infiltration. A slope of 2% on the rock is sufficient to conduct seepage to the edge of the tailings area without mounding of water to the surface. As a result, the intermediate rock will not promote infiltration in the same way that surface rock will. The filter criteria between the soil/rock and rock/soil-bentonite are not met and long term plugging is a possibility.

In summary:

- groundwater recharge of 20% of mean annual precipitation is a reasonable estimate for vegetated but not forested covers;
- recharge under forested conditions will be less;
- surficial soil texture will influence groundwater recharge but not to the extent that soil permeability would suggest;
- decreasing permeability with depth covers will increase groundwater recharge;
- covers with an intermediate drain have sufficient flow capacity to drain water to the edge of the tailings area. Clogging with time could reduce this capacity.

## IV.4.0 EVALUATION OF STABILITY METHODOLOGY FOR EMBANKMENTS

### IV.4.1 WATER EROSION (SHEET, GULLY & FLOOD)

A general discussion on uranium tailings impoundment water erosion problems has been presented in Section IV.3.1. In general, erosion release rates from embankment side slopes will be more severe than from the cap. Slope angles are greater and it is more difficult to provide a sufficient thickness of cover. In addition side slopes are susceptible to streamflow erosion at the toe and due to overtopping at the crest.

Methods for determining sheet and gully erosion have been presented in Section IV.3. These methods are equally applicable to impoundment embankments. Flood erosion techniques will be discussed in Section IV.5. Although flood erosion release rates could be very significant they will be very site-specific and it is not possible to make estimates for Canadian uranium tailings impoundments. Flood erosion will only occur due to inadequate drainage control or inadequate cover protection. Also, the magnitude of flood flow rates will be dependent on the drainage area and its hydrologic characteristics.

Estimates of 100 year embankment erosion release rates due to sheet, rill and gully erosion are presented below:

1) Soil or tailings cover: 5 to 50 metres

2) Grass cover: 1 to 5 metres

3) Grass and tree cover: 0.2 to 5 metres

### IV.4.2 WIND EROSION

Wind erosion on embankments can be estimated by the same procedures that were presented for covers in Section IV.3. The range of anticipated release rates over a 100 year period will be the same as were reported in Section IV.3, namely:

1) Soil or tailings cover: 0.1 to 1.0 metre

2) Grass cover: 0.05 to 0.5 metres

3) Trees: insignificant

However, wind erosion release rates from side slopes will be small unless prevailing winds blow towards the side slope. Unlike water erosion, the large slope angle of the side slopes will not result in increased erosion. Generally, measures to control water erosion will make wind erosion release insignificant.

### IV.4.3 VEGETATION STABILITY AND BIOLOGICAL PENETRATION

Surface stabilization of embankments with herbaceous vegetation is an accepted reclamation practice. However, because of the much greater potential for surface runoff from precipitation during the vegetation

establishment phase a more complex method of seeding is required than on flat areas. Seeds and fertilizer must be sprayed (hydroseeding) onto the embankment; both a mulch and a soil surface chemical stabilizer should be included in the spray solution. The purpose of the mulch and chemical soil surface stabilizer is to anchor the seed and fertilizer, prevent both from being washed off by precipitation, and reduce soil surface evaporation during the plant germination and establishment phases. Additional precautions must also be taken to prevent surface runoff from above the slope flooding down the slope and removing seed, fertilizer, mulch and soil stabilizer. Precautions among others include the construction of diversion barriers along the top of the embankment. A variety of erosion control practices are available to aid in vegetation establishment on embankments (U.S. Environmental Protection Agency, 1975; U.S. Highway Research Board, 1973).

Tree planting on highway cut and fill slopes is an accepted landscape practice and is not considered detrimental to long-term embankment integrity. Where drainage systems have been incorporated into embankments such as modern day tailings dams, tree root penetration of those drains and subsequently of the dam cover has been reported. Piping may occur as a result. Where individual trees have become established, windthrow, and hence possibly surface disturbance, may occur. Windthrow damage is however less likely to occur in a forest type community.

Although vegetation will control surface runoff, sub-surface seepage by surface infiltrating waters and surface erosion, it should not be considered an adequate method for controlling deep internal seepage arising within embankments. Control of such seepage is primarily one of engineering design prior to embankment construction.

### IV.4.4 PRECIPITATION AND DRAIN BLOCKAGE

In TMIII, section III.6.9, the following chemical species found in tailings pore water were identified as having a "precipitation potential" in a tailings drainage system:

- calcium salts - forming carbonate (calcite) or sulphate (gypsum),
- iron salts - sulphates (jarosite), carbonates (siderite) or hydroxides,
- manganese salts - forming carbonates (rhodochrosite) or oxides (pyrolusite), and
- silicon - forming silica (quartz) or silicates.

The rate of precipitation and the quality of precipitate generated will vary enormously. An attempt can be made, however, to put some bounds to these problems by making some estimates of the potential masses of precipitate that can be generated for a given change in the physiochemical environment, i.e., when pore water exits either into a partially full drain or via a full flowing drain to the external environment.

Using the example of iron precipitation from the four groups of salts above, Figure IV.4-1 shows that, for a small change in pH (from 5.8 to 6.2 at Eh 0.20 volts) or a small change in Eh (0.10 volts to 0.25 at pH 6), or a combination of both, the solubility of iron decreases an order of magnitude from about 100 mg/L Fe to 10 mg/L Fe. Therefore, 90 mg Fe are precipitated for every litre of water discharged to the drain. If this iron were in the form of iron hydroxide, $Fe(OH)_3$, this would amount to 57 mg of solids per litre; as jarosite, $FeSO_4$, this would be equivalent to 72 mg of solids.

A drain carrying 15 gallons per minute, i.e., 1 litre a second, could accumulate around 60 mg of solids per second if all the precipitate were to remain in the drain.

If these values are applied to a gravel underdrain with a cross section, say, of 1 m x 0.3 m, the total void space to be filled between the gravel particles at a total porosity of 40% would be 0.12 $m^3$ per metre length of the drain. Assuming equal masses for water and for the precipitate, then the void volume could be filled by precipitate, at a discharge rate of 1 litre per second, in $2 \times 10^6$ sec; i.e., 23 days. (This value could be further extrapolated to any given length of drain with a specific discharge).

The above type of calculation tends to confirm that drain blockage can be a relatively rapid process, given that the reaction rate itself is effectively instantaneous. Experience from drains in oxidizing sulphide tailings confirm that such rates of accumulation are indeed possible; drains have been known to block within 2 years of installation. Rates of potential blockage can vary from zero to a matter of months, therefore.

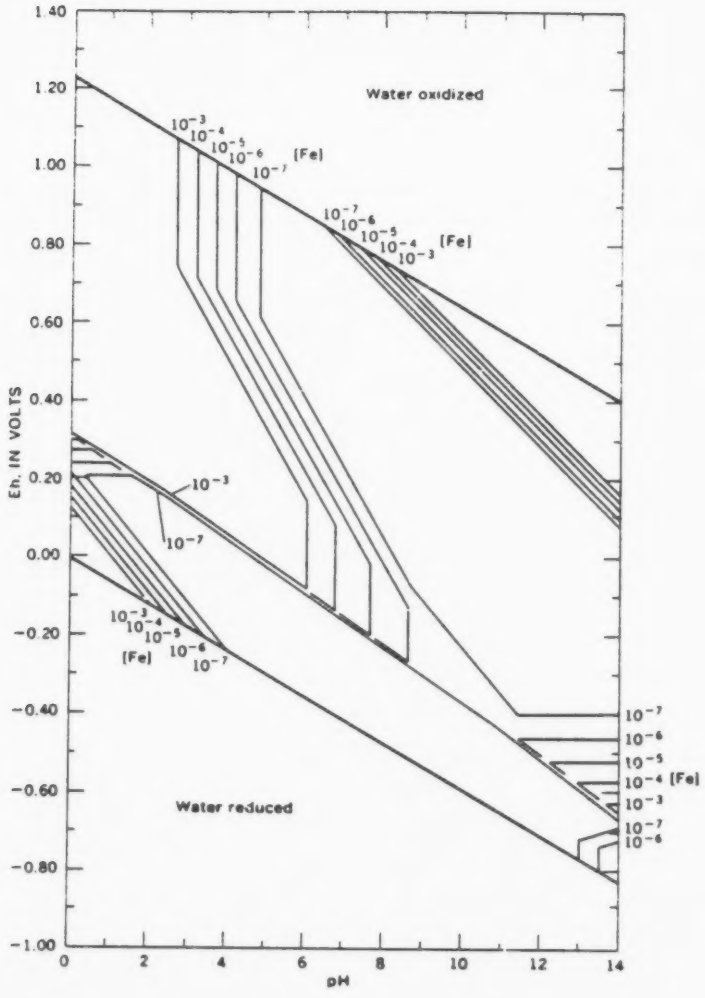
In general, the overall chemistry of the pore waters in uranium tailings would indicate that iron and calcium salt precipitation, the latter as gypsum $CaSO_4$, would be the biggest problems and manganese and silicon, not only a lesser problem, but probably at slower accumulation rates.

Insufficient work has been done to define with a certainty the potential rates of drain blockage that could occur at any specific Canadian uranium tailings site. The illustration given serves purely as a demonstration that drain blockage due to salt deposits can occur in a relatively short period relative to period of interest for long term stability.

## IV.4.5 FROST ACTION

Frost action can deteriorate water retaining embankment structures. Firstly, repeated freezing and thawing can develop a cracked structure in the embankment, increasing its permeability. Secondly, if the embankment is frost susceptible, moisture can accumulate upon freezing and, upon subsequent thaw, develop high excess pore water pressures in the embankment which reduce the slope stability.

In the uranium producing areas, clay is uncommon; therefore, available construction materials are primarily silty sand till. Bentonite additives can be used for permeability reduction.




SOLUBILITY OF IRON IN MOLES PER LITER AS FUNCTION OF Eh AND pH AT 25°C AND 1 ATMOSPHERE OF PRESSURE. ACTIVITY OF SULFUR SPECIES 96 mg/L AS $SO_4^{-2}$; AND CARBON DIOXIDE SPECIES 61 mg/L AS $HCO_3$-. (HEM, 1970)

FIGURE IV.4-1

The silty till is frost susceptible. However, because of the permeability characteristics, it can be expected to drain quite rapidly upon thaw and significant excess pore pressures are not anticipated. Thaw consolidation estimates on silt sized tailings showed little tendency for excess pressure build up and the embankments are generally coarser grained and less susceptible to pressure build up than the tailings. No signs of frost induced embankment distress has been observed in the Elliot Lake region (Denison Mines, Personal communication).

The freeze thaw behavior is illustrated somewhat by the natural slopes. In general, stable till slopes exist at a slope of 3:1. If significant excess pressures developed, the slopes would have slumped through time to a much shallower slope. Some natural slopes of 6:1 have, however, been observed in Saskatchewan.

The overall stability of embankments constructed of silty till can be expected to be relatively unaffected by frost action. As the silt content increases, the effect of frost will become a greater factor in overall stability. In pure silt embankments, Solymarr and Nunn (1983) reported significant embankment distress from frost action.

The effect of bentonite additives on frost susceptibility is unclear. The bentonite will increase the tendency for segregation and decrease the soil permeability. If the soil permeability is reduced sufficiently, little water will be able to flow to the frost front. On the thawing side, any excess pore water would develop significant excess water pressures because of the restricted drainage of the low permeability soil.

Freeze thaw calculations were carried out on the embankment soil. The depth of frost is 2.5 m and the depth of thaw is 3 m for a sandy embankment with a moisture content of 10%. The effects of slope exposure which would favour freezing on north facing exposures was not considered. Permafrost aggradation in the embankment soils is not favoured.

Available technology to protect embankments from frost induced distress consists of:

a) Flattening embankment side slopes to stable conditions. In the long-term, 6:1 slopes appear to be the minimum natural slopes that would be appropriate in Saskatchewan unless specific evaluations are done to prove otherwise. Flatter slopes would be required if an abnormally high silt content (50% plus) is present in the embankment.

b) Insulation. Insulate the embankments to limit frost penetration. One hundred millimetres of synthetic insulation will limit frost penetration to approximately 0.8 m. The long term stability of such synthetic insulation is questionable.

c) Utilizing a non-frost susceptible fill in the freezing zone and using a geomembrane for water-tightness.

d) Explore frost susceptibility of bentonite conditioned fill. Various bentonite blends could be tested for both permeability and frost susceptibility to determine the potential for heave and the probable

magnitude of excess pore water pressures upon thaw. Acceptable mixes would be defined for construction.

Each of these methods can be used alone or in combination with others on existing embankments.

IV.4.6 PHYSICAL INSTABILITY

IV.4.6.1 General

The stability of a slope can be expressed in terms of five parameters:

- slope geometry,
- engineering properties of each stratigraphic unit (shear strength and unit weight),
- location of the slip surface,
- pore water pressure conditions along the slip surface, and
- the factor of safety of the slope.

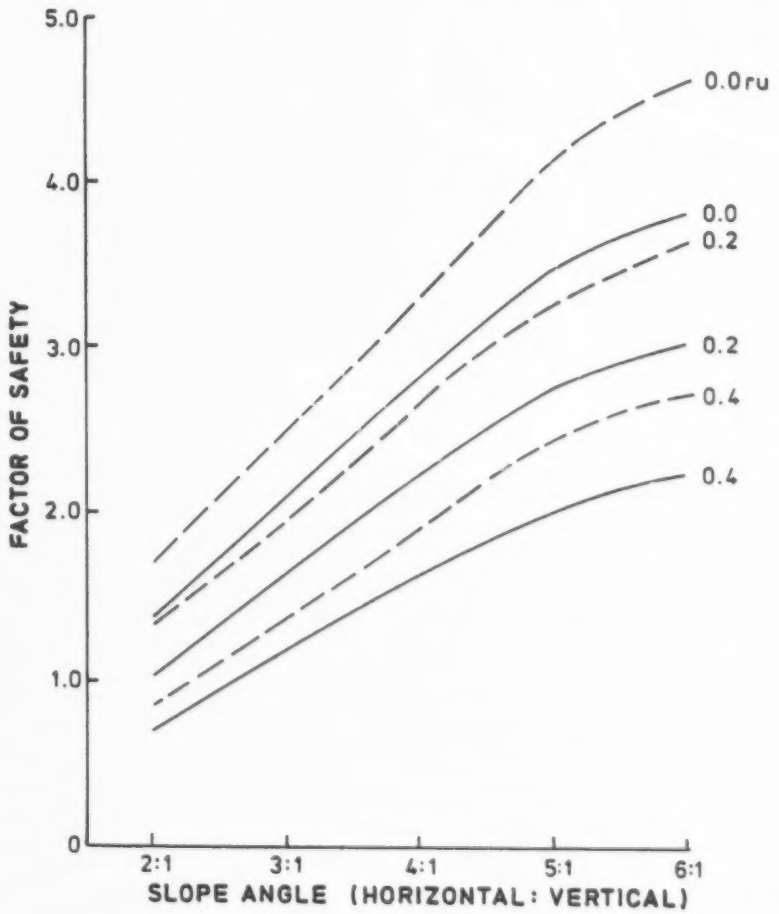
The factor of safety of a slope in this section is defined as a reduction applied to the shear strength of the soil along a slip surface being examined such that the slope is at the point of imminent failure. Changes in the factor of safety for a slope will be a function of changes in the pore water conditions within the embankment, shear strength of the embankment materials or slope geometry. The long term stability of an impoundment structure is examined relative to these factors.

IV.4.6.2 Phreatic Surface Changes

Over the life of an impoundment structure, changes in the pore water pressure conditions will be related to changes in the phreatic surface. Changes in the phreatic surface may occur as a result of changes in the permeability of the embankment materials due to factors such as plugging of soil pores, or blockage of underdrainage systems by precipitates or soil fines.

In general, an increase in the phreatic surface will result in an increase in the pore water pressure along a potential slip surface and a decrease in the factor of safety of the slope. Figure IV.4-2 illustrates the relationship between factor of safety and slope angle for various values of the pore water pressure parameter represented by ru, which is the ratio of the pore water pressure head and the overburden pressure at a point within the embankment, such that:

$$ru = (gw * hw) / (gs * hs)$$




FACTOR OF SAFETY VERSUS SLOPE ANGLE
FOR DIFFERENT PORE PRESSURE FACTORS

FIGURE IV.4-2

where:

gw = unit weight of water,
gs = unit weight of soil,
hw = height of water above the point being considered, and
hs = height of soil above the same point.

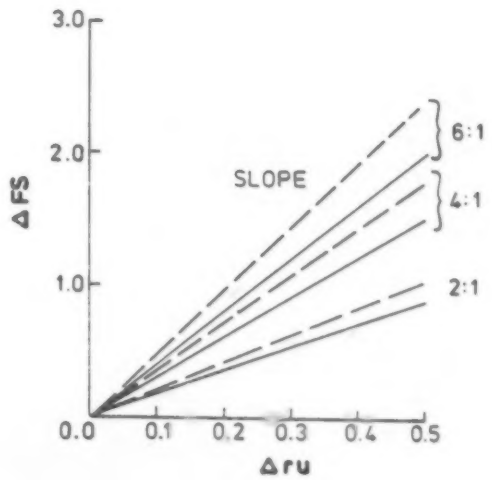
The figure is derived from stability coefficients and stability analysis charts devised by Bishop and Morgenstern (1960) and assumes a cohesionless soil. Figure IV.4-3 shows the relationship between a change in ru and a change in the factor of safety. The change in ru is proportional to the change in hw for the analysis.

IV.4.6.3 Strength Changes

Physical, chemical or biological processes may alter the embankment materials as they are exposed to a new environment with changed conditions of temperature, pressure and chemistry (Mitchell, 1976). Clays and clay shales may lose much of their stability as a result of prolonged exposure to air or as a result of rewetting. Gradual compositional changes may also occur due to exposure and weathering. For example, replacement of the dominant exchange cation and a change in the plasticity of a clay has been observed (Mitchell, 1976). For rock fills, the disintegration of interlocks due to weathering and slaking will reduce the shear strength and the stable angle of repose. For instance, well graded broken Athabasca Formation sandstone may initially be stable at angles in excess of 38 degrees, but when reduced to sand and gravel sizes by mechanical weathering and leaching, the stable angle can be expected to reduce to about 34 degrees. Similarly, the kaolinized regolith may initially be stable at a similar angle, but with time will slake to clay with a friction angle of about 25 degrees.

Leaching by groundwater can result in ion exchange or a change in the interparticle forces for clay minerals. Seepage can also cause formation of precipitates which cement particles, increasing their bond strength. A reduction in the shear strength of a soil would result from a conversion from a cohesionless soil to a soil containing a greater proportion of clay minerals. An increase in the void ratio of a soil associated with a decrease in density would also result in a decrease in the shear strength.

Local till and outwash sands used for the construction of containment embankments have had many thousands of years of weathering and as a result are stable with respect to slaking under the effects of either leachate (Clifton Associates Ltd., 1986) or groundwater. Seepage through the tailings impoundments is not expected to cause changes in the natural materials that would result in a shear strength reduction (Clifton Associates Ltd., 1986). While some change in bentonite modified soil is possible that could result in an increase in the permeability, a significant decrease in the shear strength is not anticipated. All of the commonly used cover and barrier materials are quartz rich, stable materials. It is not expected that any materials susceptible to slaking or mechanical weathering will be used in the tailings impoundments. However, a change in density may occur in near surface materials due to freeze-thaw action. The resulting increase in the void ratio would result in a




FACTOR OF SAFETY VERSUS SLOPE ANGLE FOR DIFFERENT PORE PRESSURE FACTORS

FIGURE IV.4-3

decrease in the shear strength. It is anticipated that typical changes in the shear strength would be from 41.5 degrees for the highly compacted glacial tills to approximately 35 degrees in materials subject to freeze-thaw. Similar reductions are also expected in compacted materials at all sites.

IV.4.6.4 Geometry Changes

Changes in the geometry of the impoundment structures would occur as a result of erosional forces. Typical natural slopes from 5 horizontal to 1 vertical (5:1) to 12 horizontal to 1 vertical (12:1) have been observed in overburden in uranium mining areas in Saskatchewan. These slopes represent an equilibrium condition reflecting the effect of mass movement of soil over a long period of time. A decrease in the stability of a slope would result from a steepening of the slope; an increase would be due to a flattening of the slope.

Freeze-thaw causes some small scale downslope movements of soil particles (solifluction) that would result in a flattening of the slope. Erosion occurring as a result of rilling, gullying or piping would result in a steepening of the slope. Erosion by mechanisms such as sheet erosion would result in the movement of material from a slope resulting in a flattening of the slope without causing an impression of instability as is the case with rilling or gullying (Gray and Leiser, 1982).

The erodibility of a soil is dependent upon the texture and gradation of the soil. The specifics of erosion are covered elsewhere in this document. In general, erodibility is high in uniform silts and fine sands and low in well graded gravels. It decreases with increasing clay and organic content and with low void ratios.

The fine sand, silt and lean till present in all the uranium mining areas are highly erodible by both ground and surface water. Steepening of the slopes as a result of erosion will result in a decrease in the stability.

IV.4.6.5 Summary

The influence of changing slope angles and water level in a slope are illustrated in Figures IV.4-2 and -3. The first figure shows the rapid increase in stability (Factor of Safety) that is achieved by flattening slopes in frictional materials and vice versa. The second figure shows the change in the Factor of Safety that can occur with a rise in water table. The figures show that, for instance, a dry 6:1 slope in this material (internal angle of friction = 35 degrees) would be very stable (F = 3.8); however, if erosion caused the slope to steepen to 2:1 with the water table near the slope surface (ru = 0.4) the slope would fail (F = 0.9). The effects of softening of the soil is directly proportional to the tangent of the friction angle before and after softening. The minimum desirable long term Factor of Safety, considering the worst combination of steepest eroded slope, high water table conditions and reduced soil strength is considered to be 1.5.

Most of the embankments in both Ontario and Saskatchewan are constructed with slope angles of between 2 and 4 horizontal to 1 vertical. (Refer

Section I.6.3 A and B). With the typical range of embankment materials used and their associated shear strength it is believed that current Factors of Safety with present drainage conditions are in excess of 1.5. In the absence of a rise in the phreatic surface there is little likelihood of these reducing below 1.5 in the long term. However, should drain plugging occur and should a high phreatic surface be maintained in the impoundments (as a result of infiltration) then the factor of safety would reduce. Instability of slopes steeper than 3 horizontal to 1 vertical may occur in the very long term, and such slopes should be individually evaluated to demonstrate their long term stability.

Direct release of tailings due to such failures are likely to be small. However, secondary failures and gully erosion is expected to extend the disturbed area and could become the major source of tailings release.

Seepage from the toe regions of embankments also increases the susceptibility of this region to solifluction and erosion. This may result in slope steepening and limited failure. Any failure would tend to disrupt toe drainage and this may lead to progressive failure and erosion.

IV.4.7 SEEPAGE EROSION

The following seepage erosion mechanisms and the associated analysis techniques were reviewed in TMIII:

A. Upward flow (confined flow) downstream from impoundment

   (a) Global gradient approach
   (b) Heave
   (c) Exit gradient approach

B. Unconfined flow

   (a) Global gradient approach
   (b) Exit gradient approach

It was shown in TMIII that the global gradient and exit gradient approaches for upward flow and global gradient approach for unconfined flow are the most applicable to uranium tailings impoundments. This section will give a typical example of how to apply these.

The dimensions of the idealized example are those for Key Lake shown in Figure I.6.B-2 (TMI). Under normal operating conditions, when the filter material and filter blankets behave as designed, no problems with seepage erosion are expected. However, the analysis here will assume that the filters and drains do not operate as designed. Blockage could occur due to inwashing of fines, chemical precipitates or the freezing of portions of the outlet drains. Each seepage erosion mode is evaluated below.

A. Confined flow

(a) Global gradient approach

Assume that there is very little resistance in the filter material. The length of the flow path is L = 100 m while the head loss h = 20 m, then

$$\text{Creep Coefficient } C = \frac{L}{h} = \frac{100}{20} = 5$$

$$\text{Weighted creep ratio} = \frac{\frac{L}{3} + V}{h} = \frac{\frac{100}{3} + 0}{20} = 1.67$$

From Table III.8-2, it is apparent that these values are less than the limiting values that are suggested and seepage erosion may occur. This example is used for illustration purposes only. In practice a head of 20 m would not develop against the upstream slope because of the low permeability of the tailings.

(b) Exit gradient approach

In order to estimate the factor of safety with respect to exit gradient, it is necessary to know the exit gradient. This analysis is not available and it will be assumed that the exit gradient is smaller than 0.2. The factor of safety is then:

$$Fs = \frac{i_c}{i_e} = \frac{1}{0.2} = 5$$

This value is on the low side but acceptable.

B. Unconfined flow

(a) Global gradient approach

Again, assuming very little resistance in the filter material and potential failure at the manholes, L = 60 m and Z = 20 m. Then

$$i = Z/L = 20/60 = 0.33$$

According to Table III.8-5 this gradient should not result in instability.

Although the example above is idealistic, it shows the application of the analyses presented in TMIII.

## IV.5.0 EVALUATION OF STABILITY METHODOLOGY FOR OTHER STRUCTURES

### IV.5.1 LINERS

Seepage barriers can consist of natural geologic strata or engineered barriers comprised of natural materials (soil) or membranes. This discussion will consider only engineered natural barriers or manufactured membranes. Information on the liners is taken from 2 studies conducted for the National Uranium Tailings Program: Golder Associates (1984) on the evaluation of flexible membrane liners; and, Clifton Associates Ltd. (1986) on evaluation of natural materials as seepage barriers.

#### IV.5.1.1 Hazards to Liners

The liners must be stable against both chemical attack from leachate and reagents, and physical damage due to climatic or other factors. Clifton Associates Ltd. (1986) identified four generic stages of geochemical evolution of a leachate in the tailings pond. These stages included:

- the process control stage which lasts for the operating life of the pond;
- sulphide oxidation where sulphides are present, resulting in low pH and deposition of precipitates in pore spaces;
- resolution phase where precipitates are dissolved from pore spaces in the liner;
- and, long-term phase where minor solution of soil constituents takes place at about pH 5.

The liners must be stable against chemical attack by the leachate during any one of these stages. The liners should also be able to withstand accidental spills of process reagents and hydrocarbons and the effects of radiation. In addition, the liners must be able to resist physical damage including: puncture; cold temperature shrinkage and cracking; ultraviolet degradation; degradation due to radiation; freezing and thawing consolidation; piping; and, osmotic effects.

The stability of natural and manufactured membrane liners under these influences is discussed below.

#### IV.5.1.2 Flexible Membranes

Golder Associates (1984) conducted a preliminary evaluation of 9 polymeric and 3 asphalt liner types that have been considered suitable for the physical and chemical environment in the uranium mining areas in Canada. All showed suitable chemical resistance but all were subject to installation difficulties. Asphalt showed suitably low permeabilities but was judged to be difficult to construct uniformly and was susceptible to damage due to differential movement, equipment traffic and climatic effects such as freezing and thawing. Asphaltic membranes were judged to require a soil cover to provide adequate long-term stability.

The polymeric membranes were judged to have suitable chemical resistance but were very susceptible to physical damage during installation due to vehicular traffic or improper subgrade preparation. One of the most common defects was inadequate field seaming of the membrane. The major seepage loss through manufactured membranes was judged to be primarily through liner defects. A uniform high quality installation of a polymeric liner would provide a barrier with an effective permeability of $1 \times 10^{-12}$ metres per second. However, this number would be greatly increased with an increase in the number of physical defects. No information is provided on the long-term durability and physical stability of these membranes when exposed to long-term uranium tailings seepage.

IV.5.1.3 Natural Materials

Four natural materials have been identified as potentially suitable seepage barriers. These include till, silt, peat and bentonite modified till. The chemical stability of each of these materials was examined for each of the four generic geochemical conditions. A summary of this evaluation is given in Table IV.5-1.

The anticipated long-term effects of uranium tailings leachate on the natural barriers is small. However, significant short term effects could take place in sodium saturated clays compacted wet of optimum with fresh water. Such clays are subject to ion replacement (calcium for sodium) with resulting shrinkage and increase in permeability. They are also subject to osmotic consolidation if the salt concentration in the leachate is substantially higher than that in the pore water. Osmotic consolidation will also cause shrinkage of the barrier leading to cracking and increased permeability.

In addition to the chemical durability, natural barriers must also exhibit stability under certain physical influences. The requirements for stability include:

- Adequate frost protection to prevent development of ice lenses in or under the liner. Such lensing could lead to differential heave, rupturing the liner during the freezing process, and thaw consolidation causing upward flow and release of pore water during the thawing process.

- An adequate factor of safety against piping. Since the liner may be subject to a high hydraulic gradient, the gradation of the liner and the parent material must obey accepted filter criteria. If it does not, fines may be eroded from the liner causing a rapid increase in permeability leading to uncontrollable releases.

IV.5.1.4 Summary

Little is known about the long-term behaviour of manufactured flexible membranes. It is therefore difficult to evaluate their stability over the 100 to 10,000 year time frame required. In the absence of such information, it must be assumed that these membranes will eventually degrade under the influence of chemical, physical or biological attack.

## ANTICIPATED EFFECTS OF SEEPAGE CHEMISTRY STAGE ON NATURAL BARRIER MATERIALS

| Generic Tailings Seepage Chemistry Stage | Barrier Material | | | |
|---|---|---|---|---|
| | Till* | Silt* | Clay** | Peat |
| STAGE 1:<br>Initial Stage: high pH, Ca SO4 (neutralized) tailings seepage<br><br>Duration = up to the operational life of impoundment | pH changes to 7-8. Possibilty of increased solution of sulphate. Little precipitation of aluminum. No significant effect on barrier. | pH changes to 7-8. Possibility of increased solution of sulphate. No effect on barrier if clay mineral is illite or calcium bearing. If Na clay, ion exchange with $Ca^{2+}$ cause shrinkage and increased permeability. | If sodium clay minerals, ion exchange of $Na^{+}$ by $Ca^{2+}$ with gypsum saturated solution would cause shrinking in clay and hence increase permeability. Otherwise, no appreciable effect. | pH of seepage reduced by natural pH of peat (about pH 3-5). No precipitation and probably no change in physical behaviour of barrier. |
| Stage 2:<br>Sulphide Oxidation Stage: low pH2 (acidic), high TDS tailings seepage for sulphide-bearing tailings<br><br>Duration = up to 200 yrs | Reaction with carbonate, during solution, but this precipitates gypsum in pore spaces; if aerobic, iron and aluminum precipitation. If anaerobic, no Fe: Al precipitation, net effect is reduced permeability. | As for till, but potential for long-term degradation of clay minerals to Al and Si in acidic environment, could cause increase in permeability. | Sodium clay - replacement of $Na^{+}$ with $H^{+}$, but little change in barrier permeability.<br>Calcium clay - removal of $Ca^{2+}$, replace with $H^{+}$ and increasing permeability.<br>If clay carries carbonate, neutralization produces precipitation in pore spaces and reduces permeability. | Peat leached by acidic seepage. Removal of some soluble constituents. Anaerobic reduction could cause further iron solution. Little effect on barrier, perhaps marginal increase in permeability. |
| Stage 3:<br>Resolution Stage: dominated by gypsum resolution and either pH3-4, if oxidation stage 2 occurred, due to aluminum precipitation or pH7, if no stage 2 occurred<br><br>Duration = up to 400 yrs | If Stage 2, leaching of bypsum from pore spaces. Increased permeability.<br>If no Stage 2, no effect. | If Stage 2 as for till and clay<br>If no Stage 2 as for till and clay<br>Tends to increase permeability | If Stage 2, little effect on clay minerals with possible further $Ca^{2+}$ incorporation in clays. No further effect on barrier.<br>If no Stage 2, solution of $Ca^{2+}$ from clay. Gypsum saturation decreases in the long-term. Little change to barrier. | If Stage 2, pH increase to 3-4, possibly little Al precipitation causing slight decrease in permeability.<br>If no Stage 2, pH of peat rises with infiltration, as pH of liquid drops. No effect on barrier. |
| Stage 4:<br>Long-Term Leaching Stage: infiltration rainfall/snowmelt, low TDS water at pH5<br><br>Duration = +/- 10,000yrs | pH to 5. Slow solution of residual carbonates and marginal increase in permeability. Eventual decomposition of ancillary original mineral phases in barrier. | As for till and clay | pH changes to 5. Clay minerals reach equilibrium with infiltration, initially. Eventually decomposition of clays to Al and Si. Long-term weathering of barrier and increase in permeability. | pH changes to +/-5. No significant effect on peat behaviour. |

* Behaviour function of carbonate content. Assuming 0.5 % $CaCO_3$ content in till and 5 % clays in silt

** Behaviour may be more of a function of carbonate content, than clay mineralogy.

TABLE IV.5-1

Uranium tailings leachates will affect the permeability of natural materials in the uranium mining areas, but the overall effect is expected to be small. Considering the relatively inert nature of the natural materials, it is expected that they will remain chemically stable and intact as a barrier if protected against freezing damage and against piping.

IV.5.2 DIVERSION STRUCTURES

Failure of diversion structures could occur due to:

1) scour

2) sedimentation

3) flooding

4) ice and debris blockage

Failure of a diversion structure will result in flooding of the toe or cap of the impoundment. The magnitude of this type of failure will be very site-specific and general estimates of probable release rates cannot be made. However, the magnitude of the impact can be estimated by using the MUSLE procedure discussed earlier.

A number of techniques are available to evaluate the likelihood of failure of a diversion structure due to scour and sedimentation. A brief discussion of these techniques is presented later in this chapter. The probability of failure due to flooding will depend on the design criterion used to design the structure and the degree of scour, sedimentation and/or blockage which has occurred.

If it is assumed that following construction there has been no significant change in the geometry of the diversion then the probability of failure due to flooding can be estimated by Equation 5.1:

$$f(pt,n) = 1 - (1 - 1/T)^n \qquad (5.1)$$

where T is the design return period, pt is equal to 1/T, and f(pt,n) is the probability that a T-year event will be equaled or exceeded at least once in an n-year period. If n is equal to T then f(pt,T) approaches 0.63. Therefore, there is a likelihood of 0.63 (63 percent) that the PMP will occur during a 1000 year design life. Probabilities for occurrence of other events are given in Table IV.2-1.

No suitable procedures are available for predicting the likelihood or impact of blockage due to debris and/or ice. With the development of a forest type cover it is anticipated that a considerable amount of forest debris will be produced. Some of the thickest vegetation cover may develop in and adjacent to the diversion structures. Sedimentation is expected in the flatter portions of diversions as well as behind any blockages that occur. It is anticipated that, in the absence of maintenance of the diversion structures, blockages due to sedimentation and debris will be a

regular occurrence. Ice formation and iceflows may also produce blockages in drainage ways, particularly during spring.

Once a blockage occurs the following consequential failure can result:

- flooding of a portion of the impoundment cover resulting in a killing off of vegetation cover and increased infiltration

- flow outside of the designed, erosion protected flow channel. This may result in rapid scour of the adjacent terrain and failure of the diversion structure. This will in turn result in additional scour and general erosion.

Erosion as a consequence of diversion structure failure following diversion structure blockage by debris, sediment or ice is considered to be a potential cause of major uranium tailings releases. Since this failure mode is one of successive erosion, releases can be kept small by periodic maintenance.

Channel scour could result in downstream environmental problems. However, unless scour results in failure of a diversion control embankment it will have a positive impact (in terms of the impoundment) in that it will increase the flow capacity of the diversion thus reducing the likelihood of failure due to flooding (failure in this context is defined as resulting in an adverse impact on the tailings impoundment).

Methods for determining channel and river bed scour are presented in many texts. A good account is presented by Graf (1971). The likelihood of scour or sedimentation occurring can be estimated from Figure IV.5-1. Permissible velocities for excavated and grassed waterways are presented in Table IV.5-2 and IV.5-3. Reference should be made to a text such as Graf to determine bedloads, suspended loads and total loads.

Sedimentation will occur wherever there is a reduction in flow velocity of a sediment laden flow. Reference should be made to a text such as Barfield et al (1981) to determine sedimentation rates associated with different flow control structures. A good account of sedimentation in ponds and dams is presented by Ward et al. (1978).

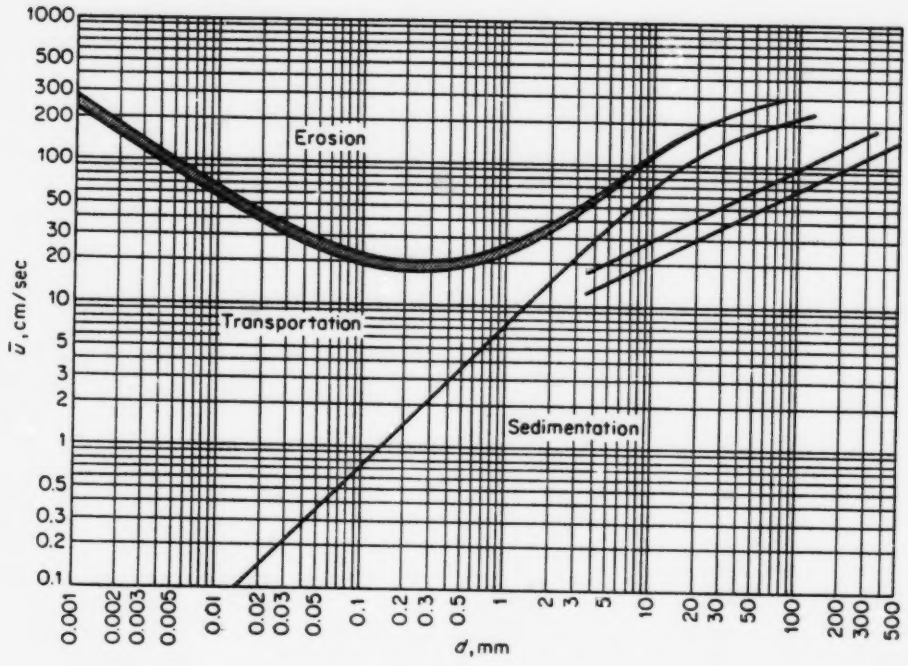
The likelihood of scour or sedimentation occurring is very site- specific and general estimates for Canadian conditions cannot be made. In general, these impacts will be severe where design practices have been poor.

## IV.5.3 SURFACE WATER QUALITY CONTROL MEASURES

Surface water quality control measures consist of a combination of the following:

- surface diversion structures to prevent surface flow towards the site from contacting the tailings or mixing with contaminated seepage or surface runoff from the impoundment,

- contaminated water storage structures required to store contaminated water until it can be treated prior to discharge,




EROSION - DEPOSITION CRITERIA FOR UNIFORM PARTICLES [AFTER HJULSTROM (1935).]

FIGURE IV.5-1

## PERMISSIBLE CANAL VELOCITIES
## [AFTER FORTIER ET AL. (1926)]

| *Original material excavated for canal* (1) | *Velocity, fps, after aging, of canals carrying** | | |
|---|---|---|---|
| | *Clear water, no detritus* (2) | *Water-transporting colloidal silts* (3) | *Water-transporting noncolloidal silts, sands, gravels, or rock fragments* (4) |
| Fine sand (noncolloidal) | 1.50 | 2.50 | 1.50 |
| Sandy loam (noncolloidal) | 1.75 | 2.50 | 2.00 |
| Silt loam (noncolloidal) | 2.00 | 3.00 | 2.00 |
| Alluvial silts when noncolloidal | 2.00 | 3.50 | 2.00 |
| Ordinary firm loam | 2.50 | 3.50 | 2.25 |
| Volcanic ash | 2.50 | 3.50 | 2.00 |
| Fine gravel | 2.50 | 5.00 | 3.75 |
| Stiff clay (very colloidal) | 3.75 | 5.00 | 3.00 |
| Graded, loam to cobbles, when noncolloidal | 3.75 | 5.00 | 5.00 |
| Alluvial silts when colloidal | 3.75 | 5.00 | 3.00 |
| Graded, silt to cobbles, when colloidal | 4.00 | 5.50 | 5.00 |
| Coarse gravel (noncolloidal) | 4.00 | 6.00 | 6.50 |
| Cobbles and shingles | 5.00 | 5.50 | 6.50 |
| Shales and hard pans | 6.00 | 6.00 | 5.00 |

* Depth of 3 ft or less.

TABLE IV.5-2

## PERMISSIBLE VELOCITIES FOR VEGETATED CHANNELS*

| Cover | Permissible Velocity, fps: Erosion Resistant Soils (% Slope) 0-5 | 5-10 | Over 10 | Easily Eroded Soils (% Slope) 0-5 | 5-10 | Over 10 |
|---|---|---|---|---|---|---|
| Bermuda grass | 8 | 7 | 6 | 6 | 5 | 4 |
| Buffalo grass<br>Kentucky bluegrass<br>Smooth brome<br>Blue grama<br>Tall fescue | 7 | 6 | 5 | 5 | 4 | 3 |
| Lespedeza sericea<br>Weeping lovegrass<br>Kudzu<br>Alfalfa<br>Crabgrass | 3.5 | NR† | NR | 2.5 | NR | NR |
| Grass mixture | 5 | 4 | NR | 4 | 3 | NR |
| Annuals for temporary protection | 3.5 | NR | NR | 2.5 | NR | NR |

* After Ree (1949).
† Not recommended.

TABLE IV.5-3

- contaminated water treatment facilities for treating the water to achieve a water quality suitable for discharge.

Given present technology and designs it is anticipated that some of the currently active or inactive tailings facilities will yield flows of surface water that are of such a quality that untreated or undiluted discharge may be inadmissible for a very long period. Examples are the acid drainage from some of the Elliot Lake impoundments (see Section I.5.8.A and Tables I.4.A-1 to 9) and the underdrainage from Key Lake (Table 1.4.B-3).

Where long term treatment is required, this requires the continuous operation of diversion works, storage facilities and a treatment plant. This requires long term care and maintenance by man. The stability of the control facilities is dependent on the continuation of this care and maintenance. The economic conditions, public concerns, institutional and governmental attitudes which will govern the basis for such long term care is highly speculative and not evaluated in this study.

Considerable effort is being directed in Canada and in other countries to develop alternative technology to long term treatment. In climatic areas where evaporation exceeds precipitation it is possible to design evaporation systems to eliminate the need for discharge (zero discharge designs). This is theoretically feasible for Saskatchewan. The long term stability of the diversion facilities and evaporation ponds for such a system remains a concern.

In areas, such as Ontario, where precipitation exceeds evaporation, methods of natural treatment such as vegetated drainage discharge areas (effectively organic filter systems) have been suggested (Hester and Associates, 1984). The potential for such systems is still highly speculative. Alternative technology is to prevent the initial generation of the contaminated waters and this has been discussed in section IV.1.6.1.

## IV.6.0 APPLICATION OF PROBABILITY TECHNIQUES TO SOME FAILURE COMBINATIONS

Figures III.9-7 to III.9-10 show fault trees for failure combinations. Probabilities of the basic failure events can be obtained by using objective or subjective approaches. In order to demonstrate the approach, the fault tree for cover failure will be evaluated.

Figure III.9-7 shows the fault tree for cover failure. Table IV.6-1 summarizes the subjective probabilities of the basic failure events. Remarks are also included on how to evaluate some of the probabilities more rigorously. The values in Table IV.6-1 are based on the assumption that the initial design was adequate.

Following the scheme given in TMIII section III.9.1.2, the combined failure probability evaluation can be done as follows:

P [Differential Settlement]

$$= P \text{ [Differential Settlement]} \; P \text{ [Flooding]}$$
$$= (0.001)(0.05) = 5 \times 10^{-5}$$

P [Chemical Attack]

$$= P \text{ [Detrimental Chemical Attack]} \; P \text{ [Flooding]}$$
$$= (0.001)(0.01) = 1 \times 10^{-5}$$

P [Frost Action]

$$= P \text{ [Detrimental Frost Action]} \; P \text{ [Flooding]}$$
$$= (0.001)(0.01) = 1 \times 10^{-5}$$

P [Cover Failure] = P [Differential Settlement] + P [Gullying] + P [Chemical Attack] + P [Sheet Erosion] + P [Wind Erosion] + P [Frost Action]

$$= 5 \times 10^{-5} + 1 \times 10^{-3} + 1 \times 10^{-5} + 1 \times 10^{-3} + 1 \times 10^{-3} + 1 \times 10^{-5}$$

$$= 3.07 \times 10^{-3}$$

Similar approaches can be followed to evaluate the other failure probabilities. It must be noted that a complete probabilistic analysis would require considerably more work than is reflected here.

TABLE IV.6-1

SUBJECTIVE PROBABILITIES OF BASIC FAILURE EVENTS IN FIGURE III.9-7

| EVENT | DISCUSSION | SUBJECTIVE PROBABILITY | HOW TO EVALUATE PROBABILITIES BETTER |
|---|---|---|---|
| Differential Settlement | - Assume that this event occurs due to large settlement caused by unsaturated flow consolidation (a problem not foreseen during design). | 0.001 | - Perform detailed settlement analyses, using all possible mechanisms and consider influence if some are neglected. |
| Flooding | - Flooding leading to dispersion of tailings following differential settlement is assumed to be associated with the 1 in 200 year flood. | 0.05 | - Perform detailed flow analysis as well as gully and other erosion analyses. |
| Gullying | - Concentrated flow causing excessive local erosion, despite good design | 0.001 | - Perform complete analysis following Falk, et al (1985), propagating uncertainty throughout the analysis |
| Detrimental Chemical Attack and Frost Action | - Consider these as unforeseen events and therefore of low probability. | 0.001 | - Difficult to evaluate in more detail |
| Flooding | - Once chemical attack or frost action has occurred a relatively small flood may cause cover failure | 0.01 | - Perform erosion analysis based on degraded cover |
| Sheet Erosion and Wind Erosion | - Consider degradation of cover with time, the probability will therefore change with time. | 0.001 (assumed after say 50 years) | - Use USLE or other erosion analysis |

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# APPENDIX IV.1.1

# VEGETATION TO CONTROL PYRITE OXIDATION

## APPENDIX IV.1.1 VEGETATION TO CONTROL PYRITE OXIDATION

Vegetation establishment has been implemented on uranium tailings in which pyrite oxidation may be considered to have reached an advanced stage in the surface to 30 cm depth, which would be considered the major zone of root development and activity for the type of species seeded to form a vegetative cover. No reports have been encountered of vegetation studies on recently deposited tailings, either under laboratory or field conditions, in which pyrite oxidation reactions would not yet have been expected to occur.

It would not be feasible to attempt to establish vegetation on absolutely new tailings such as those discharged at the Quirke mine, for prior to discharge they are treated with lime to adjust the discharge slurry to a pH of 9.5 (Hester and Associates, 1984). Quirke tailings are, however, now turning acidic and the time frame over which this occurs is expected to be within the time period between end of deposition and start of soil stabilization (Rio Algom Ltd., personal communication).

Current experience dictates that tailings originating from nickel (Peters, personal communication), base metal and precious metal (Watkin, personal communication) operations be allowed to age for between one and three years before considering the establishment of vegetation on them. The aging period is required to permit breakdown and leaching of mill chemicals present in the tailings at deposition. It is not known what length of aging period is required for uranium tailings where a far less intensive chemical treatment (numbers and types of chemicals) occurs in ore processing.

The rationale behind the use of vegetation to reduce the rate of pyrite oxidation or acid generation in tailings has been expressed by Caruccio (1976). Beneficial effects of revegetation can be exemplified by calculating the amount of alkalinity that may be produced using the partial pressure of carbon dioxide that can be expected in the pore spaces of a good soil mulch that is formed during vegetational development processes. Under those conditions, $pCO_2$ in the soil pores can be as high as 0.1 and infiltrating water coming in contact with this gaseous medium absorbs additional amounts of carbon dioxide which effectively enhances the dissolution of calcium carbonate. In that case, alkalinities as high as 481 mg/L as $HCO_3^-$ (788 mg/L as $CaCO_3$) can be generated which can effectively neutralize about eight times more acidity than the alkalinities generated under atmospheric $pCO_2$. That increase in alkalinity, generated by the increases in carbon dioxide of the soil atmosphere, underscores the need for the rapid blanket revegetation in reclamation efforts.

Alkalinity and pH can be controlled by reclamation efforts. Basic chemical compounds or calcareous strata capable of producing alkalinity can be incorporated within the near surface horizons that will form the vegetational substrate. If a blanket vegetation cover is then developed upon the calcareous material, which will effectively enhance the production of alkalinity of infiltrating waters, an alkaline front will

be generated which will migrate downward into potentially acidic horizons. In addition to affording a neutralizing front this alkaline zone will tend to ameliorate the acid producing mechanisms, displace the iron bacteria, and in time enhance the overall reclamation efforts of the mine.

Several lysimeter type studies have been reported where under either laboratory or field testing conditions, vegetative cover has been established on acid tailings from various metal ore sources. Generally, the conclusion has been drawn that a vegetative cover does not reduce either pyrite oxidation or acid seepage. A detailed examination of those studies reveals severe deficiencies in one or more aspects including experimental design, type and quality of the vegetative cover and interpretation of data that can be obtained from such "lysimeter" experiments. In the majority of those experiments, inadequate neutralization and fertilizer treatments did not result in the level of root development, and hence organic matter development, considered necessary to develop the type of soil atmosphere envisaged by Caruccio (1976). In that respect, the recent studies by Silver (quoted in Hester and Associates, 1984) on the potential role of organic matter, as represented by muskeg, in reducing pyrite oxidation are much more demonstrative and meaningful.

It may be suggested that vegetation established on tailings which have already begun to oxidize in the upper surface levels will not be effective in preventing further pyrite oxidation and acid seepage unless relatively high levels of neutralizing agents are incorporated just prior to seeding. There are two reasons for suggesting that. Firstly, pyrite oxidation may have proceeded to the stage of developing more total acidity in the tailings than can be effectively neutralized by the volume of alkalinity that can theoretically be generated in the system presented by Caruccio (1976). Secondly, by the time of vegetation establishment and development of a sufficiently effective organic matter horizon, pyrite oxidation may already be occurring at a depth below which any effect of root/organic matter can be considered effective.

At the time revegetation investigations were begun on the Nordic and Lacnor tailings disposal areas, pyrite oxidation in the tailings was (subjectively) well advanced in both time and depth. Therefore, any vegetative cover would not be able to develop a sufficient level of alkalinity to neutralize the amount of acidity already generated. Also, vegetation establishment on the tailings area was conducted on a piecemeal basis. In some locations, a "good" level of establishment was achieved; in others, only "poor" establishment was obtained. It is not unreasonable to argue that by the time the Nordic tailings area, for example, had been revegetated, the level of acidity generated across the tailings area and to depth as well, was, and still is, sufficient to provide an acid seepage situation that will persist for many decades.

The one major question arising from this discussion concerns the potential role of vegetation in preventing pyrite oxidation when established on "fresh" tailings. At what time period after deposition a revegetative cover could be established directly on, say, Quirke tailings, is presently unknown. If, however, pyrite oxidation could be

prevented for a sufficiently long period of time (whatever) by the presence of a neutralizing agent such as agricultural limestone, fly ash, cement kiln dust or rock phosphate until such time as the tailings have matured to permit vegetation establishment, then it may be possible to envisage a more beneficial effect from a vegetative cover on a tailings area than has been recorded to date. That supposition, however, requires experimental verification.

# APPENDIX IV.1.2

# CHEMICAL TREATMENT TO PREVENT ACID GENERATION

## APPENDIX IV.1.2 CHEMICAL TREATMENT TO PREVENT ACID GENERATION

One of the first reported studies on inhibition of pyrite oxidation by phosphates was by Dutch researchers in the early 1950's (Quispel, Harmsen and Otzen, 1952). Studying pyrite oxidation in agricultural soils from the Dutch Polders, they noted that pyrite was not always oxidized on exposure to the atmosphere. Through laboratory work, they determined that non-oxidation was due to the presence of phosphate. The level of phosphate required to inhibit oxidation appeared highly critical.

A United States patent filed in 1963 claimed that the use of any inorganic phosphate source (phosphate ore, phosphate slime by-products) would prevent the oxidation of pyrite and marcasite occurring in coal spoils. The phosphate was claimed to act by converting the iron sulphide to calcium sulphate and ferrous phosphate ($Fe_3(PO_4)_2$). The ferrous phosphate, being insoluble, precipitates out and eventually provides a phosphate coating around the sulphide mineral grains. Formation of iron phosphate precipitates in place of iron sulphate was also recorded by the Dutch workers mentioned above.

Murakami (1968) noted that phosphate (form not specified) greatly retarded the oxidation of pyrite when the oxidation medium had a neutral pH, but when the medium pH was lowered to pH4, there was no effect of phosphate on oxidation retardation.

None of the above investigations appeared to receive much attention from those concerned with the control of acid mine drainage or acidic tailings seepage. Not until the early 1980's was the possibility of using phosphate material as a pyrite oxidation control mechanism reconsidered when Stiller (1983) revived the concept for potential use in acidic coal mine spoils occurring in the eastern United States of America.

Several studies have been conducted on the effect of various silicates on pyrite oxidation. The most widely known is that conducted by Tyco Laboratories (1971). Extensive investigations were conducted on the effect of treating sulphide-containing coal refuse piles with sodium silicate and silica-alumina gel. Tyco Laboratories concluded in part that neutralization of coal mine refuse by treatment with waterglass (sodium silicate) was an effective technique for preventing or minimizing acid mine drainage (AMD) generation for a period in excess of 3000 mm (120 inches) of equivalent rainfall. Also, sealing a coal mine refuse pile surface to water percolation with silicate-based gel was effective in preventing or minimizing AMD generation over a long period, perhaps in excess of 10,200 mm (400 inches) of equivalent rainfall.

Surface gels are not, however, stable to extremes in temperature. Both heating and freezing cause coagulation of the gel with the resultant loss in continuity. Such broken gels no longer seal the refuse, but the residual effects of the treatment minimize the generation of AMD over a prolonged period of time, similar to the effect of neutralizing the material with silicate.

A study by Nebgen and Weatherman (1979) reported on the inhibition of acid mine drainage formation from underground coal mines. Experimental results from three pyrite materials indicated that quantities of acid mine drainage can be substantially reduced if soluble iron III (ferric) iron is controlled. The best inhibitors were neutral or alkaline siliceous materials such as fly ash, blast furnace slag, Portland cement, and cement kiln dust. These materials appeared to insolubilize iron III species to make them unavailable for reaction with pyrite. The data strongly suggested that the soluble ferric iron aqueous was a key oxidant for pyrite to produce acid mine drainage.

Other researchers have observed that coating pyrite with alkaline silicate will reduce formation of acid mine drainage. However, results have been interpreted as being due to exclusion of oxygen from the pyritic surface rather than true chemical inhibition. Nebgen and Weatherman (1979) consider their data to suggest that such coatings are real chemical inhibitors rather than coatings to exclude air.

Recently, an investigation was undertaken to assess the potential use of various phosphate and silicate chemicals to prevent the oxidation of iron sulphides (pyrite and pyrrhotite) in non-oxidized and oxidized mill tailings from a number of Canadian mining operations (Watkin, 1985).

The inhibition of iron sulphide oxidation in mill tailings by phosphate and silicate compounds was demonstrated but the relationship between inhibition and chemicals was not, however, a straightforward one. From the study it was clear that the degree of inhibition was not similar for tailings obtained from various sources; also any particular phosphate or silicate compound was not universally effective.

Previous studies on the inhibition of iron sulphide oxidation in coal mine spoils and acid sulphate soils have tended to present a simplistic state of affairs. Generally these studies have been confined to a very limited number of materials which contain iron sulphides, i.e., two or three coal mine spoils or two or three acid sulphate soils. Within these studies, fairly sharp end points have been demonstrated between the material concerned and the amount of chemical needed to inhibit iron sulphide oxidation. The wider range of materials evaluated by Watkin (1985) (with variables occurring in origin, type of iron sulphide present, amount of iron sulphide and particle size constitution) amply demonstrated that there will not be a simple and straightforward solution to the prevention of iron sulphide oxidation by the addition of phosphate and silicate chemicals.

The variable responses recorded have numerous parallels in the known variable responses of mill tailings to amendments added. Numerous studies have demonstrated that each mill tailings has to be considered unique from a revegetation viewpoint, and a specific program or recipe formatted for each mill tailings area (e.g., Watkin and Watkin, 1982). Given the limited knowledge obtained in the study by Watkin (1985), the indications are that the inhibition of iron sulphide oxidation could also be site specific in terms of type of chemical which is effective and the rate at which it must be applied.

Of the phosphatic chemicals evaluated, the bone meals, apatites and potassium phosphates were the most effective in preventing acidic conditions developing in test containers. One of these chemicals could be effective with a particular mill tailings, but quite ineffective on another. The reasons for such variability were not understood. Both the bone meals and apatite are relatively insoluble in water compared to the relatively high solubility of potassium phosphate.

Several phosphatic materials were ineffective in maintaining acceptable pH levels in the various test trials, namely monobasic calcium phosphate and several agricultural phosphate fertilizers (superphosphate and triple superphosphate). The use of such materials, appeared in most instances to enhance the development of acid conditions. These materials when added to agricultural soils do not create or increase acid conditions in the soils. It is dubious however, if a fair comparison can be made between the physio-chemical environment of agricultural soils and the environment presented by tailings slurries in a controlled environment.

Six sodium silicate chemicals were very effective in raising the pH of highly acid tailings from three mining properties. Thereafter the maintenance of the pH levels achieved was dependent upon the type of sodium silicate and the rate at which it was applied. An assessment of the reasons for the variable effectiveness of the sodium silicates indicated a very strong correlation with sodium silicate solubility. The two most effective sodium silicates, judged by persistence of effectiveness, were the least soluble of the six forms evaluated.

At this stage of understanding, it is not possible to conclude that the use of either phosphate or silicate chemicals would provide a means of permanently preventing iron sulphide oxidation in mill tailings. At this point though, it is possible to consider the use of both types of materials as a means of preventing oxidation over the short term. At many mine properties, tailings disposal practice is to dispose of tailings to a particular section of the disposal area for a period of time and then move disposal to one or more other portions of the area, before returning to the first area again and repeating the disposal cycle. Depending upon the time period between repeated disposal it would theoretically be possible to treat the tailings with phosphate or silicate chemicals so as to prevent the onset of iron sulphate oxidation. Considerably more investigation would have to be undertaken though, in the laboratory and in the field, to verify the possibility suggested above.

The effect of treating mill tailings with mixtures of phosphate and silicate chemicals should be considered the next most important step in attempting to derive a technology for the prevention of iron sulphide oxidation in mill tailings. Presently it would be feasible to treat mill tailings with either a phosphate or a silicate chemical, where it has been demonstrated by a laboratory evaluation, that a particular chemical is effective for the mill tailings in question (the economics of treating a mill tailings as such, has not yet been precisely determined.). A study of phosphate-silicate mixtures is necessary to determine a) if there is a synergistic effect arising from the use of

such mixtures, b) if a longer lasting or permanent effect on inhibiting iron sulphide oxidation could be achieved and c) if use of such mixtures would increase or decrease the cost of treating mill tailings.

# APPENDIX IV.3.1

# EROSION RELEASE RATE EXAMPLE

## APPENDIX IV.3.1 EROSION RELEASE RATE EXAMPLE

It is required to determine the total erosion from a Canadian uranium impoundment over a period of 1000 years. About 50 years of rainfall information is available at the location of the impoundment and it has been established that typically the following major events occur on an annual basis:

1) 10 storm events with an average depth of 5 mm
2) 5 storm events with an average depth of 10 mm
3) 3 storm events with an average depth of 15 mm
4) 2 storm events with an average depth of 20 mm
5) 2 storm events with an average depth of 25 mm
6) 1 storm event with an average depth of 30 mm

There is no upstream catchment contributing to the cap or the side slope of the impoundment. It is required to determine side slope:

1) cover erosion losses (water and wind)
2) gully incision
3) cover protection requirements.

A typical side slope to be evaluated has a crest width of 500m, length down the slope of 50m and 2:1 side slopes.

Additional information that has been obtained through field and laboratory testing are:

1) particle size distribution of the soil cover material
2) uniformity coefficient $C_u$ of 10
3) coarse granular structure
4) moderate permeability

Based on regional flood frequency information the following 24 hour duration flood rainfall depths have been obtained:

1) 2 year return period: 35 mm
2) 5 year return period: 40 mm
3) 10 year return period: 50 mm
4) 20 year return period: 70 mm
5) 50 year return period: 100 mm
6) 100 year return period: 150 mm
7) PMP event: 400 mm

It is proposed to obtain solutions by using the following procedures which are discussed in Chapter 3:

Water Erosion: USLE and MUSLE
Wind Erosion: Wind erosion equation
Gully Incision: Method of Falk et al. (1985)
Cover Requirements: Tractive force approach

Each of these solutions is presented below.

Water Erosion

Step 1 will be to use the USLE to determine average annual erosion.

From regional map information an average annual rainfall value R of 50 has been determined. The length slope factor LS is determined by using Equation 3.6. In the equation m is 0.5, L is 165 feet (50 m) and x is 0.447. The LS factor is estimated as about 23. If it is assumed that the side slope is grassed and there is a 75 percent ground cover the CP factor is estimated as about 0.03 from Table IV.3-1.

The erodibility factor, K, is estimated from the nomograph presented in Figure IV.3-2. Inputs to the nomograph are:

1) Organic matter content of 2%
2) Percent silt and very fine sand 30%
3) Percent sand 50%
4) Soil structure 3
5) Permeability 4

From the nomograph it is established that K has a value of 0.2.

Substituting these values into the USLE equation it is estimated that average annual erosion losses will be about 7 tons/acre/year or about 17.5 tonnes/hectare/year. Assuming a bulk density of 1.5 it is estimated that 1.75 mm of material will be lost each year. Total losses over a 1000 year period would therefore be about 1.8 metres.

However, the USLE was developed to estimate annual and seasonal losses from agricultural fields. It does not adequately account for severe flood events. Over periods of 1 to 20 years it should be anticipated that the procedure will give reasonable estimates of gross erosion. For periods of 100 to 1000 years it will probably be necessary to use a procedure which will account for single severe events. The MUSLE is such an approach and will be used in step 2.

Step 2: Application of the MUSLE single event procedure.

As discussed previously a storm runoff procedure needs to be used in conjunction with the MUSLE. For this example the WASHMO computer model will be used. Inputs and outputs from the model for the PMP event are presented in Appendix IV.3.2. Curve numbers for the side slope were estimated from Table IV.3-2.

By making a series of computer evaluations for different rainfall depths the following erosion rates were estimated:

| Rainfall (mm) | Sediment Yield (tonnes) | Frequency (years) | Total Yield (tons/acre) | Total Yield (tonnes/hectare) |
|---|---|---|---|---|
| 5 | 0.00 | annual (10 times) | 0 | 0 |
| 10 | 0.00 | annual ( 5 times) | 0 | 0 |
| 15 | 0.00 | annual ( 3 times) | 0 | 0 |
| 20 | 0.30 | annual ( 2 times) | 600 | 1500 |
| 25 | 2.40 | annual ( 2 times) | 4800 | 12000 |
| 30 | 5.70 | annual ( 1 time) | 5700 | 14250 |
| 35 | 9.40 | 1 in 2 years | 4800 | 12000 |
| 40 | 14.30 | 1 in 5 years | 2960 | 7400 |
| 50 | 25.80 | 1 in 10 years | 2580 | 6450 |
| 70 | 54.40 | 1 in 20 years | 2720 | 6800 |
| 100 | 106.50 | 1 in 50 years | 2130 | 5325 |
| 150 | 207.60 | 1 in 100 years | 2080 | 5200 |
| 400 | 805.00 | PMP event | 800 | 2000 |
| TOTAL | | | 29170 | 72925 |

However, there are a number a severe events which have not been considered (200 year, 500 year, etc.) and it is suggested that the total be increased by 25 percent. The 1000 year total sediment yield is therefore estimated as 36000 tons/acre (90,000 tonnes/ha). The depth of material lost is estimated as about 9 metres.

It can be seen that the average annual erosion rate based only on the annual events is about 11 tons/acre (27.5 tonnes/ha). While the average annual rate based on all events is over 30 tons/acre (75.0 tonnes/ha). Both these rates are somewhat higher than the estimate of 7 tons/acre (17.5 tonnes/ha) obtained through use of the USLE. If the USLE is used as a better estimate of average annual rate the MUSLE results can be adjusted ("calibrated") by multiplying them by 7/11. This approach would give a cover loss of nearly 6 metres (7/11 of 9 metres).

Note also that a greater percentage of vegetative cover should be achievable with mature forest type cover in Saskatchewan and Ontario and erosion rates may be reduced to a small fraction of the rates estimated in this example.

Wind Erosion Losses

Wind erosion losses can be estimated by using the information presented in Chapter IV.3.2. From the soil cover particle size distribution it is established that about 56 percent of the material has a diameter larger than 0.84 mm. From Table IV.3-3, the soil erodibility factor, I', is determined to be 25. From available map information the average annual climatic factor, C', is estimated as 50.

If it is assumed that the roughness factor, K', is equal to 1.0 then the factor $E_3$ (I'K'C') has a value of 12.5. If the prevailing wind direction is parallel to the side slope crest then the flow path L' is about 1640 feet (500 metres) and Figure IV.3-9 can be used to obtain $E_4$. The movable

$E_3$ scale is placed along the ordinate so that 12.5 on the movable scale corresponds to 50 (the average annual C' factor). Then by moving around an interpolated 12.5 curve until it intersects 1640 feet (500 m) an $E_4$ value can be obtained. This value is estimated as about 8 tons/acre/annum (20 tonnes/ha/annum).

If it assumed that there is no grass residue left on the side slope then the annual wind erosion rate will be 8 tons/acre/annum (20 tonnes/ha/annum). If vegetative residue is left on the side slope then it is necessary to use Figures IV.3-9 and IV.3-10. For example if 500 lbs/acre (560 Kg/ha) of residue are left then the V factor will have a value of 200 to 1000 depending on the cover type. Assuming a value of 500 it is estimated from Figure IV.3-10 that annual erosion rates will be 7 tons/acre (17.5 tonnes/ha).

Over a 1000 year period the cover loss due to wind erosion would be about 2 metres. Total release rates due to sheet, rill, and wind erosion would be about 5 metres.

Gully Incision

In addition to sheet, rill and wind erosion it might be expected that a number of gullies would form. The procedure of Falk et al. (1985) will be used to make approximate estimates of the maximum depth of incision of the gullies.

From the historical rainfall information it is seen that there are 13 events per year with more than 0.5 inches (13 mm) of rainfall. Converting all dimensions into English units the geometry of the side slope is:

1) horizontal length of 147 feet (45 m)
2) vertical height of 73.3 feet (22.3 m)
3) side slope length of 164 feet (50 m)
4) side slope of 2:1

Using Equation 3.8 the drainage density area is estimated as 12.12 $ft^2/ft$ (3.69 $m^2/m$) and the drainage area is 1988 $ft^2$ (185 $m^2$). The stable side slope is then estimated, by using Equation 3.10 as 0.3%. The coefficient G is determined from Figure III.2-12 and has a value of 2.5. This value is inserted into Equation 3.11 and the transient slope is calculated to be 11.2%

The occurrence is obtained from Figure III.2-13 and by using Equation 3.12 the maximum depth of incision is determined. The depth of incision after 200 years is estimates as 25.4 ft. (8 m). From Equation 3.13 the width of the gully is estimated as about 6 ft. (2 m) and the maximum depth will occur about 74 feet (23 m) above the toe.

It might be expected that during a 1000 year period the gullies would widen and become deeper. However, it seems unlikely that depths in excess of 30 ft. (10 metres) below the surface would be achieved. It has been established that the surface itself could be eroded by about 15 ft. (5 metres) due to sheet and wind erosion. It is anticipated therefore that a number of gullies would be formed and that they might exhibit depth of

incision of 30 to 50 ft. (10 to 15 metres) below the original cover surface.

Cover Protection Requirements

Riprap requirements can be determined by using the tractive force approach.

If the side slope is treated as a wide open channel, with a bed slope of 0.5 and a width of 500m, the depth of flow and flow velocity can be determined by using Manning's equation.

The peak flow rate for the PMF has been estimated by using the WASHMO program and is 2.5 $m^3/s$. Assuming a Manning's n of 0.02 the depth of flow will be 0.005 m and the flow velocity 1.0 $m^3/s$.

For a wide open channel the tractive force can be determined as:

$$r = wyS$$

where r is the unit tractive force, w is the unit weight of water, y is the depth of flow, and S is the slope. Substituting in the previously determined values the permissible tractive force is estimated as about 2.4 $Kg/m^2$ (0.5 $lb/ft^2$). Using Figure III.2-14 it is determined that 30 mm diameter riprap will need to be placed on the lower portion of the side slope.

# APPENDIX IV.3.2

# WASHMO OUTPUT FOR PMP EVENT

**APPENDIX IV.3.2 WASHMO OUTPUT FOR PMP EVENT**

```
*********************************************************
*                                                       *
*     H Y D R O L O G I C A L   S Y S T E M S           *
*                                                       *
*********************************************************
*                                                       *
*           PROGRAM  -  WASHED                          *
*                                                       *
*           WATERSHED MODELLING                         *
*                                                       *
*       PROGRAM TO DETERMINE RUNOFF HYDROGRAPHS         *
*       AND SEDIMENTGRAPHS FOR SMALL CATCHMENTS         *
*                                                       *
*********************************************************

COMPANY DOING ANALYSIS :   SRK
ENGINEER               :   Andy Ward
DATE                   :   5-MAR-86
CLIENT                 :   CANMET
PROJECT DESCRIPTION    :   Uranium Tailings Cov
MAJOR WATERSHED NAME   :   Sideslopes

THE INPUT DATA FILE IS                    :soil.pmp
THE FLOOD HYDROGRAPH AND SEDIMENTGRAPH IS NOT STORED

**********************************************************************
WATERSHED CONDITIONS AT  Sideslopes
**********************************************************************

GLOBAL PARAMETERS
-----------------

RAINFALL                                    (mm.)   :     400.00
INITIAL ABSTRACTION                         (mm.)   :        .00
  -- will default to the SCS method
TIME INCREMENT OF HYDROGRAPH FROM START OF RUNOFF   :        .10

RAINFALL DISTRIBUTION SELECTED                      :SCS TYPE 2 CURVE
```

**********
SUBWATERSHED CONDITIONS AT SIDESLOPES
**********

RAINFALL PARAMETERS
---

| | | | |
|---|---|---|---|
| SCS CURVE NUMBER | | : | 80.00 |
| UNIT HYDROGRAPH SELECTED | | : | DOUBLE TRIANGLE |

MAP PARAMETERS
---

| | | | |
|---|---|---|---|
| AREA | (ha.) | : | 2.50 |
| HYDRAULIC LENGTH | (m.) | : | 50.00 |
| PERCENT FOREST | (%) | : | .00 |
| PERCENT AGRICULTURE | (%) | : | .00 |
| PERCENT GRASSLAND | (%) | : | 75.00 |
| OVERLAND FLOW SLOPE | (%) | : | 50.00 |
| CHANNEL SLOPE | (%) | : | 1.00 |
| CHANNEL LENGTH FROM SUBWATERSHED | (m.) | : | .00 |
| TYPE OF CHANNEL FROM SUBWATERSHED | | : | A NATURAL STREAM |
| CORRECTION FACTOR FOR IMPERVIOUS AREA | | : | 1.00 |
| CORRECTION FACTOR FOR CHANNEL IMPROVEMENTS | | : | 1.00 |
| AREAL REDUCTION FACTOR | | : | 1.00 |

SEDIMENT PARAMETERS
---

| | | | |
|---|---|---|---|
| SOIL ERODIBILITY PARAMETER K | | : | .20 |
| OVERLAND FLOW LENGTH | (m.) | : | 50.00 |
| OVERLAND FLOW SLOPE | (%) | : | 50.00 |
| COVER OR CONSERVATION PRACTICE FACTOR | | : | .03 |
| SPECIFIC GRAVITY OF THE SEDIMENT PARTICLES | | : | 2.65 |
| EXPONENT OF THE FLOW SEDIMENT LOAD RELATIONSHIP | | : | 2.00 |

PARTICLE SIZE DISTRIBUTION OF SEDIMENT FLOW
---

| PART. SIZE mm. | % FINER % |
|---|---|
| .000 | .0 |
| .001 | 5.0 |
| .010 | 10.0 |
| .100 | 20.0 |
| 1.000 | 50.0 |
| 10.000 | 100.0 |

********* STORM HYDROGRAPH GENERATED FROM START OF RAINFALL **********

| TIME * | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|---|---|---|---|---|---|---|---|---|---|---|
| .0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 1.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 2.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 3.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 4.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 5.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 6.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 7.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 8.0 * | .0 | .0 | .0 | .0 | .1 | .1 | .1 | .1 | .1 | .1 |
| 9.0 * | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| 10.0 * | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| 11.0 * | .1 | .1 | .1 | .2 | .3 | .4 | .5 | 1.2 | 1.6 | 2.2 |
| 12.0 * | 2.5 | 1.1 | .3 | .2 | .2 | .2 | .2 | .2 | .2 | .2 |
| 13.0 * | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 |
| 14.0 * | .2 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| 15.0 * | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| 16.0 * | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| 17.0 * | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| 18.0 * | .1 | .1 | .1 | .1 | .1 | .0 | .0 | .0 | .0 | .0 |
| 19.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 20.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 21.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 22.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 23.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |

| | | | |
|---|---|---|---|
| INITIAL ABSTRACTION | = | 12.70 | mm. |
| ROUTED FLOW TIME FROM THE SUBWATERSHED | = | .00 | hours. |
| TIME TO PEAK OF UNIT HYDROGRAPH | = | .05 | hours. |
| THE DEPTH OF WATER ON WATERSHED | = | 314.10 | mm. |
| VOLUME OF RUNOFF | = | 7.85 | thousand cu.m. |
| PEAK RUNOFF RATE | = | 2.55 | cu. m./sec. |
| TIME TO PEAK RUNOFF | = | 12.05 | hours. |

****** STORM SEDIMENTGRAPH GENERATED FROM START OF RAINFALL **********

| TIME * | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|---|---|---|---|---|---|---|---|---|---|---|
| .0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 1.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 2.0 * | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| 3.0 * | 1.0 | 3.4 | 5.8 | 8.4 | 10.8 | 13.5 | 16.0 | 18.8 | 21.4 | 24.4 |
| 4.0 * | 27.0 | 30.1 | 32.8 | 36.1 | 38.9 | 42.3 | 45.2 | 48.8 | 51.7 | 55.5 |
| 5.0 * | 58.5 | 62.4 | 65.5 | 69.7 | 72.8 | 77.1 | 80.4 | 84.9 | 88.2 | 92.9 |
| 6.0 * | 96.3 | 101.1 | 104.6 | 109.7 | 113.2 | 118.5 | 122.1 | 127.6 | 131.3 | 136.9 |
| 7.0 * | 140.7 | 146.5 | 150.3 | 156.4 | 160.3 | 166.5 | 170.4 | 176.9 | 180.9 | 187.5 |
| 8.0 * | 191.6 | 198.4 | 202.5 | 209.5 | 213.7 | 220.9 | 225.1 | 232.5 | 236.8 | 244.4 |
| 9.0 * | 248.7 | 256.4 | 260.8 | 268.8 | 273.2 | 281.3 | 285.8 | 294.1 | 298.6 | 307.1 |
| 10.0 * | 311.6 | 320.3 | 324.9 | 333.7 | 338.3 | 347.3 | 352.0 | 361.1 | 365.8 | 376.1 |
| 11.0 * | 381.2 | 493.9 | 537.7 | 1061.2 | 1266.0 | 1832.3 | 2064.5 | 5337.2 | 6696.5 | 9509.5 |
| 12.0 * | 10676.1 | 3643.1 | 1055.1 | 1022.7 | 1011.5 | 979.1 | 967.9 | 934.9 | 923.4 | 890.7 |
| 13.0 * | 879.2 | 846.1 | 834.4 | 801.3 | 789.5 | 756.2 | 744.3 | 710.9 | 699.0 | 665.5 |
| 14.0 * | 653.5 | 412.5 | 324.9 | 321.0 | 319.6 | 315.8 | 314.4 | 310.5 | 309.1 | 305.3 |
| 15.0 * | 303.9 | 300.0 | 298.6 | 294.8 | 293.4 | 289.5 | 288.1 | 284.2 | 282.8 | 279.0 |
| 16.0 * | 277.6 | 273.7 | 272.3 | 268.4 | 267.0 | 263.2 | 261.8 | 257.8 | 256.4 | 252.5 |
| 17.0 * | 251.1 | 247.2 | 245.8 | 241.9 | 240.5 | 236.6 | 235.2 | 231.2 | 229.8 | 226.0 |
| 18.0 * | 224.6 | 220.7 | 219.3 | 215.3 | 213.9 | 209.9 | 208.5 | 204.7 | 203.3 | 199.4 |
| 19.0 * | 197.9 | 194.0 | 192.5 | 188.6 | 187.2 | 183.3 | 181.9 | 178.0 | 176.6 | 172.6 |
| 20.0 * | 171.1 | 167.2 | 165.8 | 161.9 | 160.5 | 156.5 | 155.1 | 151.2 | 149.8 | 145.8 |
| 21.0 * | 144.3 | 140.5 | 139.1 | 135.1 | 133.6 | 129.8 | 128.3 | 124.4 | 122.9 | 119.0 |
| 22.0 * | 117.6 | 113.6 | 112.1 | 108.3 | 106.8 | 102.9 | 101.5 | 97.6 | 96.1 | 92.1 |
| 23.0 * | 90.7 | 86.8 | 85.4 | 81.3 | 79.9 | 76.0 | 74.6 | 70.6 | 69.2 | 65.4 |

| | | | |
|---|---|---|---|
| SEDIMENT YIELD | = | 804.85 | tonnes. |
| PEAK SEDIMENT CONCENTRATION | = | 3643.12 | mg/l. |
| TIME TO PEAK SEDIMENT CONCENTRATION | = | 12.05 | hours. |

## STORM HYDROGRAPH FOR WATERSHED SIDESLOPES

| | | | |
|---|---|---|---|
| TOTAL AREA OF THE WATERSHED | = | 2.50 | ha. |
| THE DEPTH OF WATER ON WATERSHED | = | 314.12 | mm. |
| VOLUME OF RUNOFF | = | 7.85 | thousand cu.m. |
| PEAK RUNOFF RATE | = | 2.55 | cu. m./sec. |
| TIME TO PEAK RUNOFF | = | 12.05 | hours. |
| TIME INCREMENT OF NEW HYDROGRAPH | = | .10 | hours. |
| NUMBER OF RUNOFF VALUES | = | 209 | |

******* STORM HYDROGRAPH GENERATED FROM START OF RUNOFF *******

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| .0 | .0 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| .1 | .1 | .3 | .3 | .5 | .5 | 1.6 | 1.6 | 2.5 | 2.6 |
| .3 | .3 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 |
| .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 | .2 |
| .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 | .1 |
| .1 | .1 | .1 | .1 | .0 | .0 | .0 | .0 | .0 | .0 |
| .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |
| .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 | .0 |

STORM SEDIMENTGRAPH FOR WATERSHED Sideslopes

TOTAL SEDIMENT YIELD = 804.85 tonnes.
PEAK SEDIMENT CONCENTRATION = 10754.07 mg/l.
TIME TO PEAK SEDIMENT CONCENTRATION = 12.20 hours.

********* STORM SEDIMENTGRAPH GENERATED FROM START OF RUNOFF ********

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 4.6 | 7.0 | 9.6 | 12.0 | 14.8 | 17.2 | 20.2 | 22.6 | 25.8 | 28.2 |
| 31.6 | 34.1 | 37.6 | 40.1 | 43.9 | 46.4 | 50.4 | 53.0 | 57.2 | 59.8 |
| 64.2 | 66.8 | 71.5 | 74.1 | 79.1 | 81.7 | 86.9 | 89.5 | 95.0 | 97.6 |
| 103.3 | 105.9 | 111.9 | 114.5 | 120.8 | 123.4 | 129.9 | 132.5 | 139.4 | 142.0 |
| 149.0 | 151.6 | 159.0 | 161.6 | 169.1 | 171.7 | 179.6 | 182.2 | 190.3 | 192.8 |
| 201.2 | 203.8 | 212.4 | 215.0 | 223.9 | 226.4 | 235.5 | 238.0 | 247.5 | 250.0 |
| 259.6 | 262.0 | 272.0 | 274.4 | 284.6 | 286.9 | 297.4 | 299.7 | 310.5 | 312.8 |
| 323.7 | 326.0 | 337.2 | 339.4 | 350.9 | 353.1 | 364.7 | 366.9 | 380.1 | 382.2 |
| 535.7 | 539.5 | 1257.2 | 1274.4 | 2047.4 | 2080.4 | 6600.0 | 6776.1 | 10578.8 | 10754.1 |
| 1054.6 | 1055.6 | 1011.0 | 1012.0 | 967.5 | 968.3 | 923.1 | 923.7 | 878.9 | 879.4 |
| 834.1 | 834.6 | 789.3 | 789.7 | 744.1 | 744.4 | 698.8 | 699.1 | 653.4 | 653.6 |
| 324.9 | 324.9 | 319.6 | 319.6 | 314.4 | 314.4 | 309.1 | 309.2 | 303.9 | 303.9 |
| 298.6 | 298.7 | 293.4 | 293.5 | 288.1 | 288.1 | 282.8 | 282.9 | 277.6 | 277.6 |
| 272.3 | 272.3 | 267.0 | 267.0 | 261.8 | 261.8 | 256.4 | 256.4 | 251.1 | 251.1 |
| 245.8 | 245.9 | 240.5 | 240.5 | 235.2 | 235.3 | 229.8 | 229.8 | 224.6 | 224.6 |
| 219.2 | 219.3 | 213.9 | 213.9 | 208.5 | 208.5 | 203.3 | 203.3 | 197.9 | 198.0 |
| 192.5 | 192.5 | 187.2 | 187.2 | 181.9 | 181.9 | 176.6 | 176.6 | 171.1 | 171.1 |
| 165.8 | 165.8 | 160.5 | 160.5 | 155.1 | 155.1 | 149.8 | 149.8 | 144.3 | 144.3 |
| 139.1 | 139.1 | 133.6 | 133.6 | 128.3 | 128.3 | 122.9 | 123.0 | 117.6 | 117.6 |
| 112.1 | 112.1 | 106.8 | 106.8 | 101.4 | 101.4 | 96.1 | 96.1 | 90.7 | 90.7 |

PARTICLE SIZE DISTRIBUTION OF SEDIMENT

WEIGHTED SPECIFIC GRAVITY = 2.65

| PART. SIZE mm. | % FINER % |
|---|---|
| .000 | .0 |
| .001 | 5.0 |
| .010 | 10.0 |
| .100 | 20.0 |
| 1.000 | 50.0 |
| 10.000 | 100.0 |

## APPENDIX IV.3.3

## WIND EROSION CLIMATIC FACTORS

(Maps showing the distribution of Climatic Factor C' for the U.S.A. are included here as none have been developed for Canada)

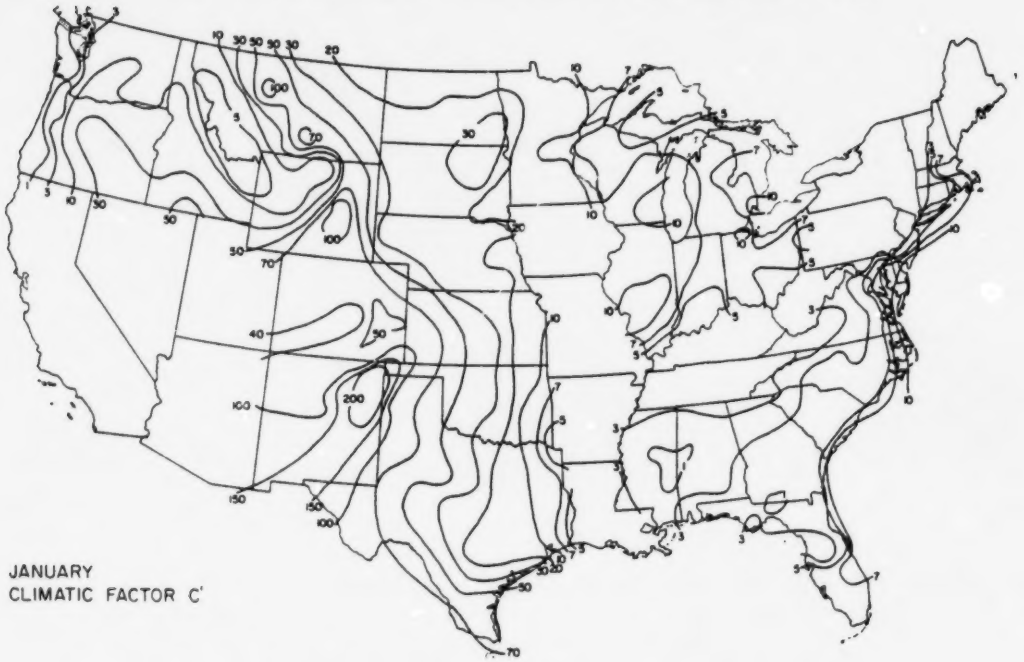


FIGURE 11.—Wind erosion climatic factor $C'$ (percent) for January.

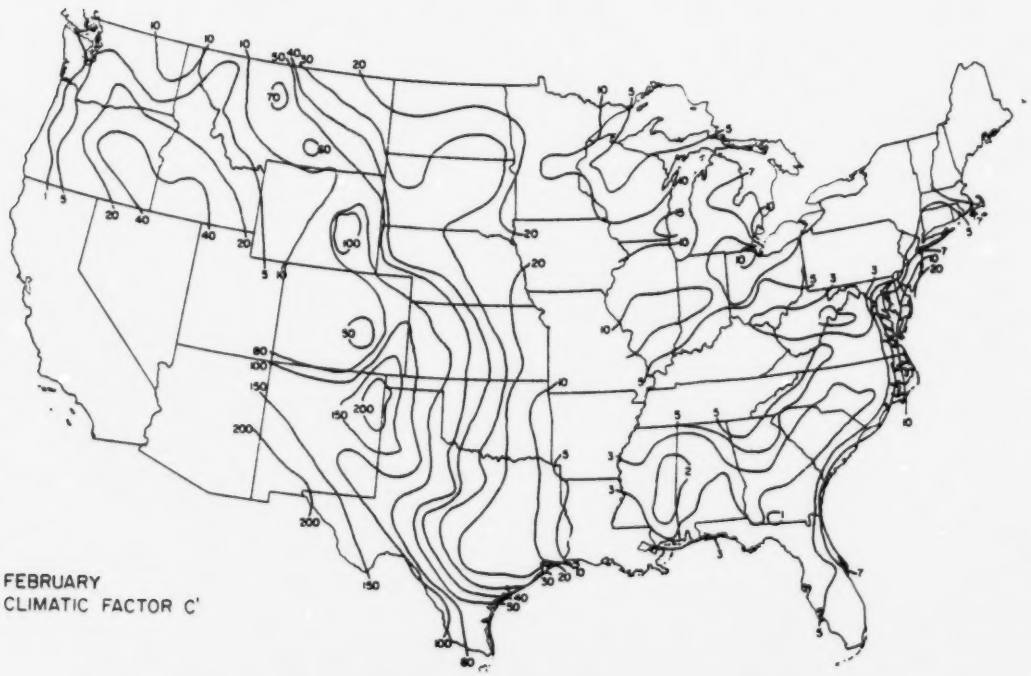


FIGURE 12.—Wind erosion climatic factor $C'$ (percent) for February.

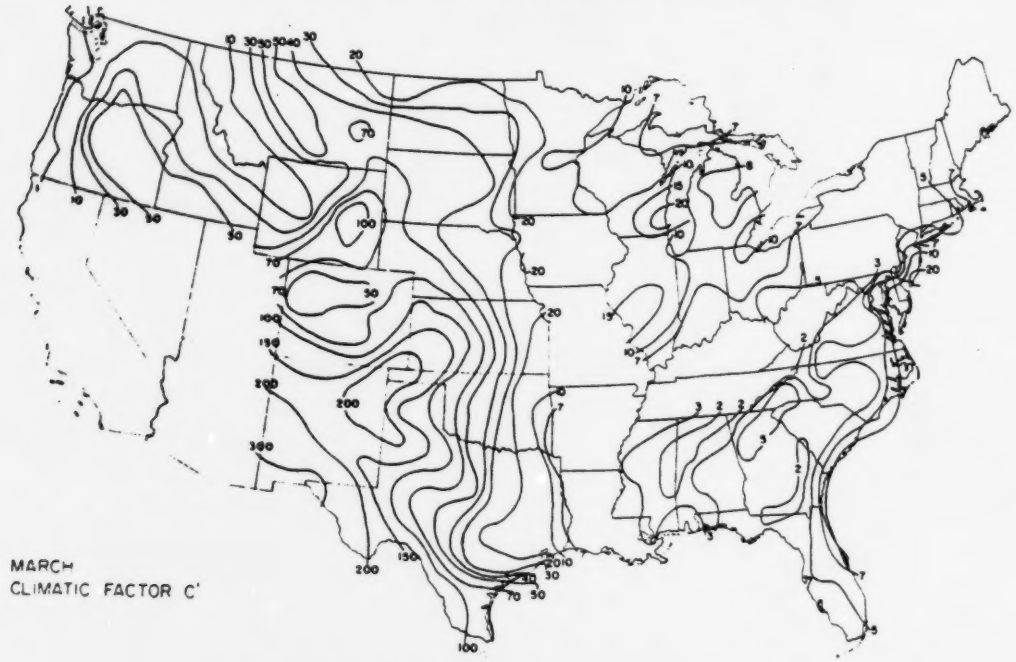


FIGURE 13.—Wind erosion climatic factor *C'* (percent) for March.

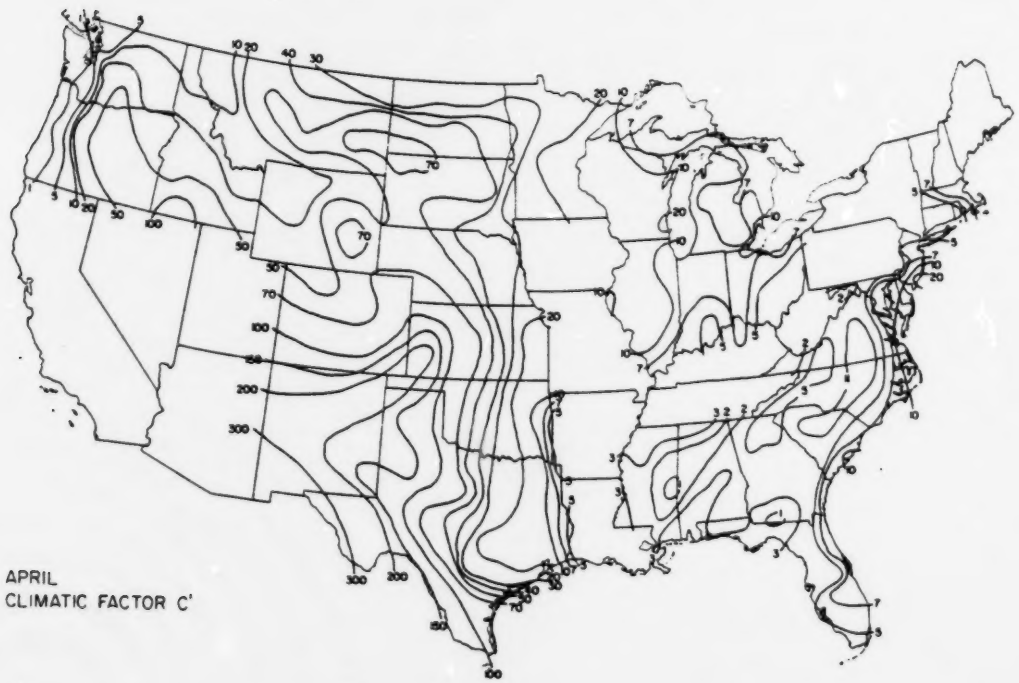


FIGURE 14.—Wind erosion climatic factor *C'* (percent) for April.

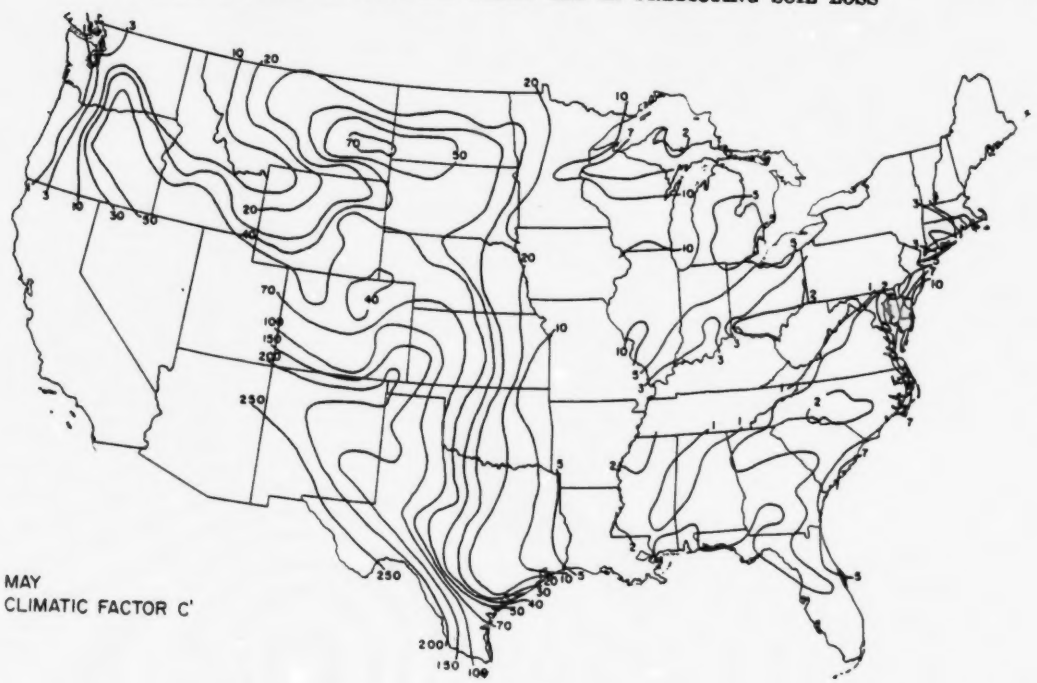


FIGURE 15.—Wind erosion climatic factor $C'$ (percent) for May.

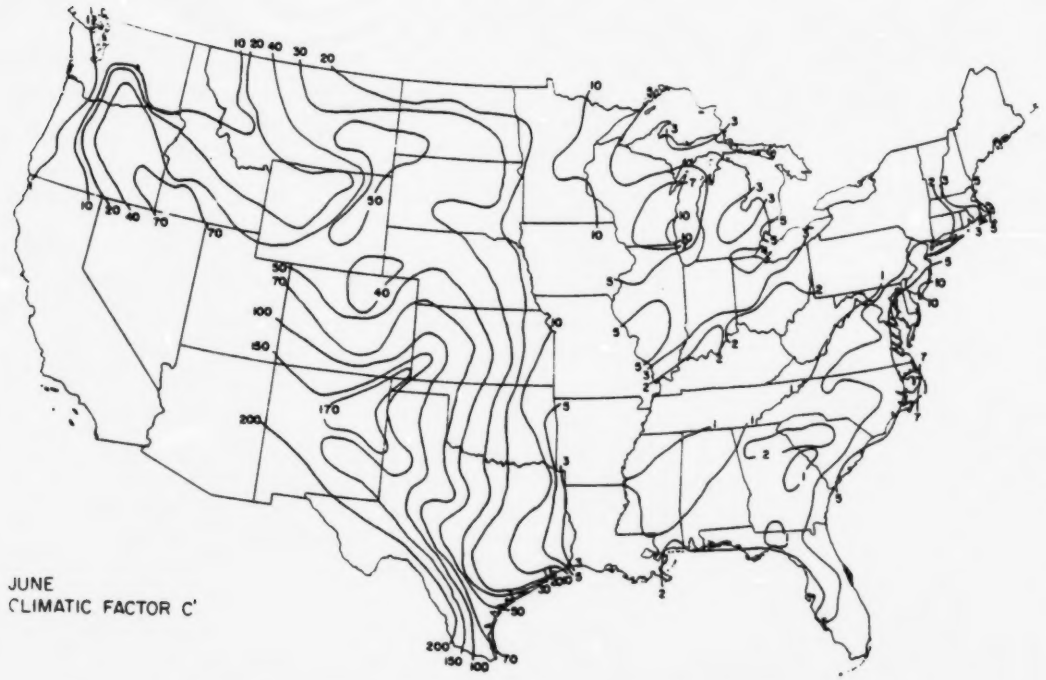


FIGURE 16.—Wind erosion climatic factor $C'$ (percent) for June.

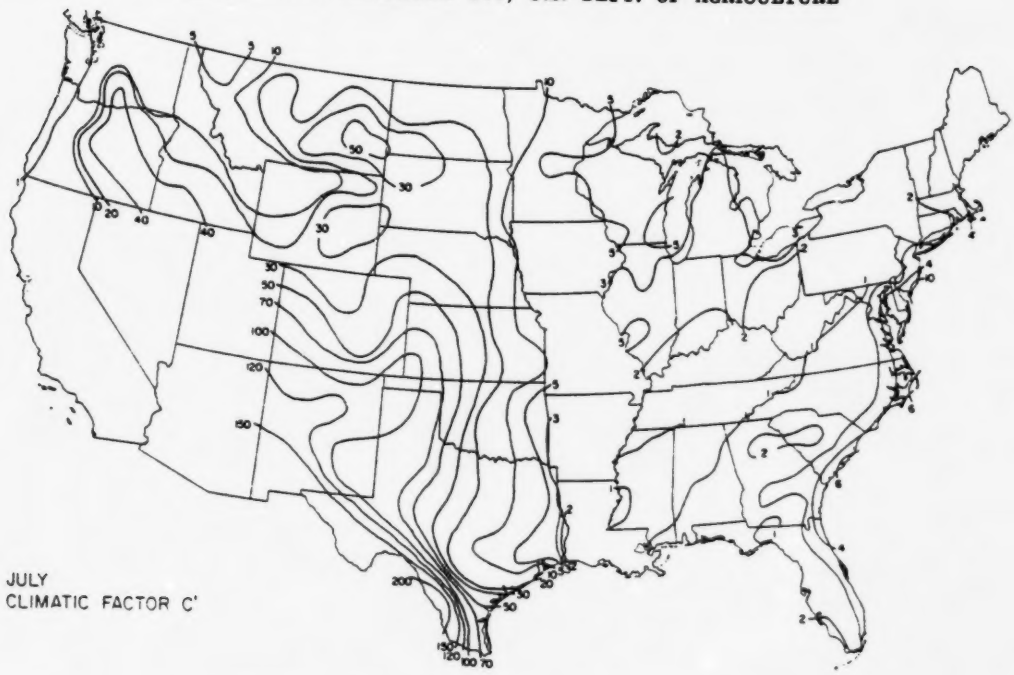


FIGURE 17.—Wind erosion climatic factor $C'$ (percent) for July.

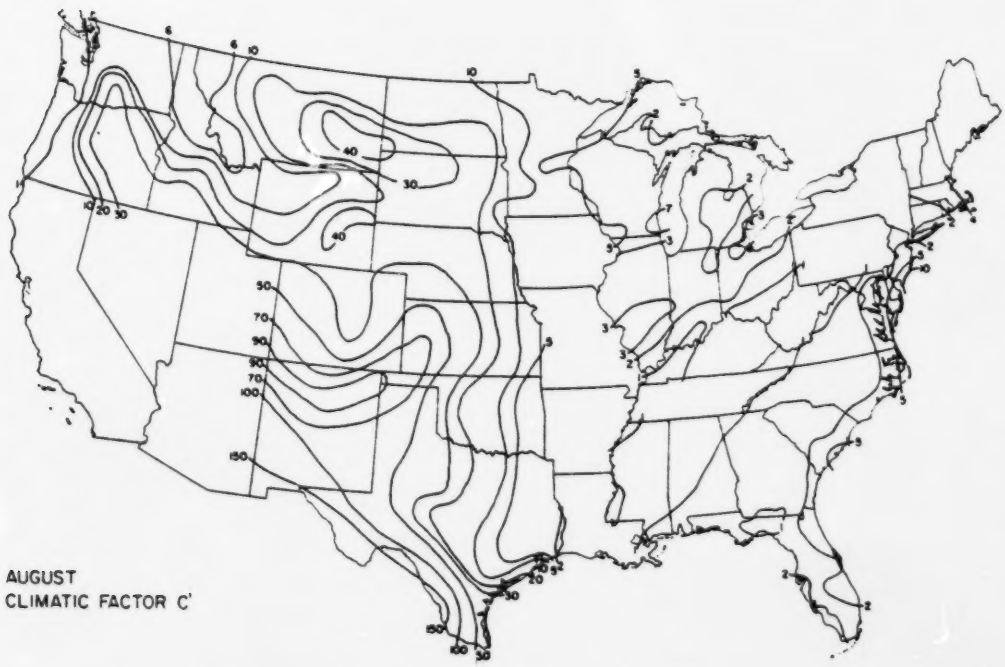


FIGURE 18.—Wind erosion climatic factor $C'$ (percent) for August.

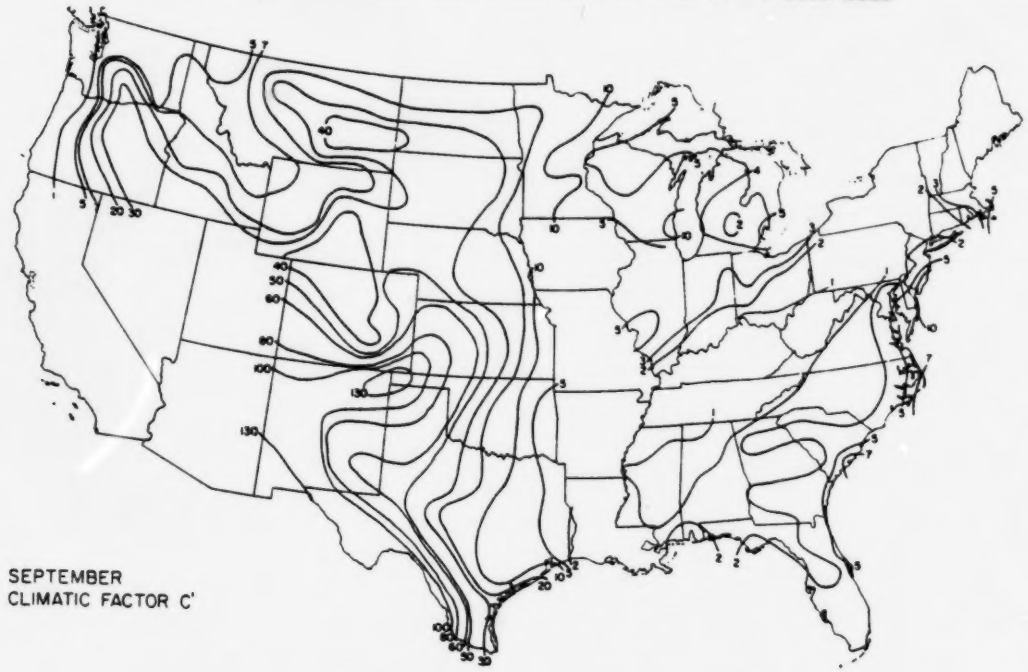


FIGURE 19.—Wind erosion climatic factor $C'$ (percent) for September.

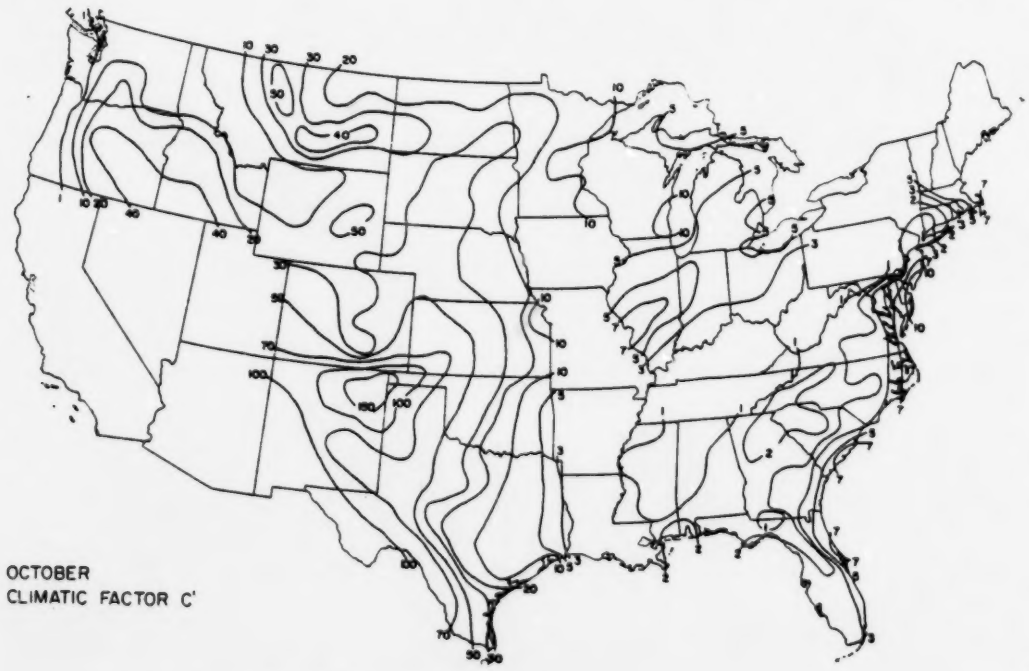


FIGURE 20.—Wind erosion climatic factor $C'$ (percent) for October.

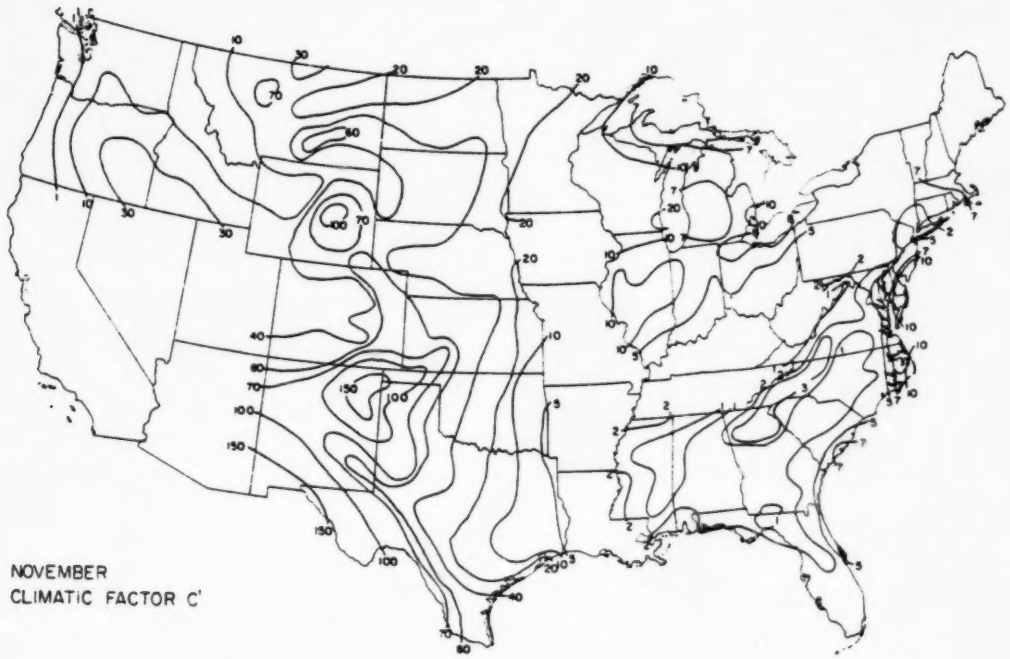


FIGURE 21.—Wind erosion climatic factor $C'$ (percent) for November.

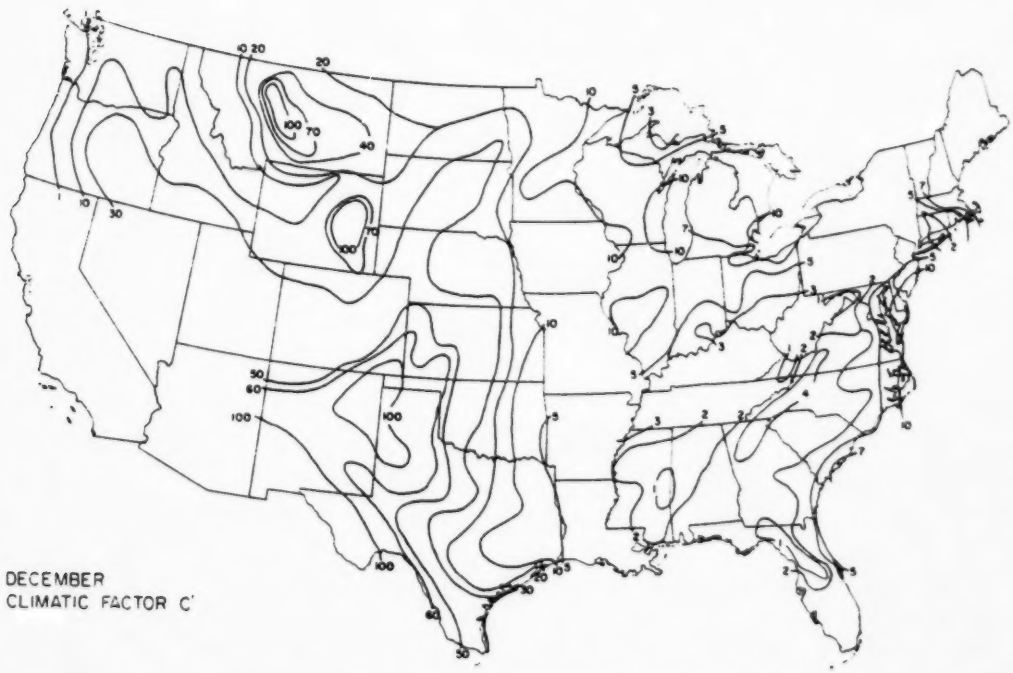


FIGURE 22.—Wind erosion climatic factor $C'$ (percent) for December.